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DESIGN, DURABILITY AND LOW-COST PROCESSING
TECHNOLOGY FOR COMPOSITE FAN EXIT GUIDE VANES

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16. Abstract A program was conducted to design, fabricate and test a durable, low cost, lightweight composite fan exit guide vane for high bypass ratio gas turbine engine application. Eight candidate material/design combinations were evaluated by NASTRAN finite element analyses. A total of four combinations were selected for further analytical evaluation, part fabrication by two vendors and fatigue test in dry and wet condition. A core and shell vane design was chosen in which the unidirectional graphite core fiber was the same for all candidates. The shell material, fiber orientation and ply configuration were varied. Material tests were performed on raw material and composite specimens to establish specification requirements. Pre-test and post-test microstructural examination and nondestructive analyses were conducted to determine the effect of material variations on fatigue durability and failure mode. The program provided relevant data with respect to design analysis, materials properties, inspection standards, improved durability, weight benefits and part price of the composite fan exit guide vane.					
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FOREWORD

This report presents the results of a twelve-month technical effort to design, fabricate and evaluate a durable, low-cost composite fan exit guide vane for high bypass ratio gas turbine engine application. This program was conducted for the National Aeronautics and Space Administration, Lewis Research Center, under Contract NAS3-21037.

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1.0 SUMMARY

The objectives of the subject program were to design, fabricate and test a durable, low cost, light weight composite fan exit guide vane for high bypass ratio gas turbine engine application. The subject program established design requirements, identified fiber and resin materials candidates and developed process control and inspection procedures.

During the program, eight candidate material/design combinations were evaluated by NASTRAN finite element analyses; four combinations were selected for further evaluation, part fabrication and test. A core and shell design was chosen in which the unidirectional graphite core fiber was the same for all candidates and the shell material, fiber orientation and ply configuration were varied. The shell construction wrapped around the core at the trailing edge and terminated under the aluminum leading edge sheath in all four designs.

Material tests were performed on raw material, consolidated test panels and sections removed from vanes to establish specification requirements for raw material and part fabrication. Pre-test and post-test microstructural examinations and nondestructive analyses were conducted on the parts to determine the effect of variations in part quality on durability. Comparisons were made between different epoxy novalac resin systems and fabrication procedures selected by the two vendors participating in the program.

Equivalent numbers of vanes were fabricated by Composites Horizons and TRW. Tool trial vanes were dimensionally inspected to confirm tool configuration. Several vanes were inoculated with intentional flaws to establish nondestructive inspection standards. The balance of vanes were evaluated under static loading conditions and high cycle fatigue tested to failure to establish part durability in "dry" and "wet" condition.

Conclusions drawn from program data are summarized below in the following categories: design analysis, improved durability, materials properties, inspections standards, weight benefits and part price.

- o A correlation was established between NASTRAN analysis, static and dynamic strain gage data and modes of failure for each of the material/ply orientation vane configurations tested. All four thick trailing edge composite fan exit guide vane configurations exhibited fatigue strain capability at failure in excess of established requirements. Two of the material/ply orientation combinations, with reduced shell ply stiffness, exhibited increased fatigue margin compared to stiffer shell configurations. A correlation was shown to exist between vane fatigue failure mode and torsional stiffness. Vanes produced by two vendors and fabricated using different processes, epoxy

material, and shell fibers showed similar fatigue performance behavior. The presence of some fiber wrinkling and higher levels of porosity evident in one vendor's product did not affect part fatigue life. Composite vane polyurethane coating integrity and bond interface strength were not degraded during fatigue testing under dry or wet conditions.

- o Experimental data substantiated the computer model developed for predicting moisture weight gain in composite fan exit guide vanes expected from service operation. The presence of up to 0.8 weight percent moisture in composite vanes did not affect fatigue performance.
- o Mechanical property tests of four lots of 345 GPa (50 M) modulus Fortafil 5A Great Lakes Carbon fiber revealed good repeatability and acceptable properties. Infrared signature and glass transition temperature characterization were established for resin systems. These data were used to establish a materials and process specification to provide for improved product control.
- o Low voltage radiography and visual examination were effective in identifying intentional flaws in as-fabricated vanes. Radiography was also effective in detecting cracks in post-fatigue test vanes.
- o Composite vanes provide a 24.2 kgs (53 lbs) weight saving compared to aluminum vanes in a typical JT9D engine.
- o Composite vane price, based on projections of 1000 vanes/month production, was determined to be cost effective based on price-to-weight comparisons of composite to current bill-of-material aluminum.

2.0 INTRODUCTION

Fan exit guide vanes are utilized in high bypass ratio gas turbine engines to redirect fan air flow downstream of fan blades. The redirection of fan air reduces aerodynamic drag and improves efficiency. These high aspect ratio vanes are designed to withstand aerodynamic forces and experience no significant engine structural loads.

Significant weight reduction benefits can be achieved by substituting advanced nonmetallic composite parts for current aluminum vanes. The primary technical challenge, leading to successful incorporation of this composite part, is through the design and fabrication of a durable, low cost, light weight vane using advanced composite material.

Experience with graphite composite fan exit guide vanes during the early 70's revealed a combination of fiber material, process and design deficiencies which resulted in inadequate part durability. The subject program was directed at those critical factors believed to influence durability. Significant improvements in both vane design and materials/processing were demonstrated.

The subject program consisted of three tasks directed at 1) vane design for composite materials, 2) vane fabrication to demonstrate inspectable, improved quality, light weight and low cost parts at two fabricators using different materials and processes, and 3) fatigue testing to demonstrate increased durability of a wraparound shell concept on a thick trailing edge vane. All objectives of this contract were achieved.

3.0 DESIGN, MATERIAL SELECTION AND ANALYSIS

3.1 VANE DESIGN CONSIDERATIONS AND MATERIALS SELECTION

3.1.1 Introduction

Fan exit guide vanes in JT9D model engines are located downstream of the fan blades in the fan bypass duct (Figure 3-1). In this position, the vanes turn fan air in the axial direction to reduce aerodynamic drag and improve engine operating efficiency. The vanes are designed to withstand aerodynamic forces and experience no significant engine structural loads. Failure or loss of a vane during engine operation would have no effect on the reliability of engine operation. Individual vanes are positioned in cast aluminum platforms using polyurethane as a means of bonding the vane in position. Various JT9D engine models use from 84 to 108 vanes per engine. The quantity and size of vanes are determined by aerodynamic and noise requirements.

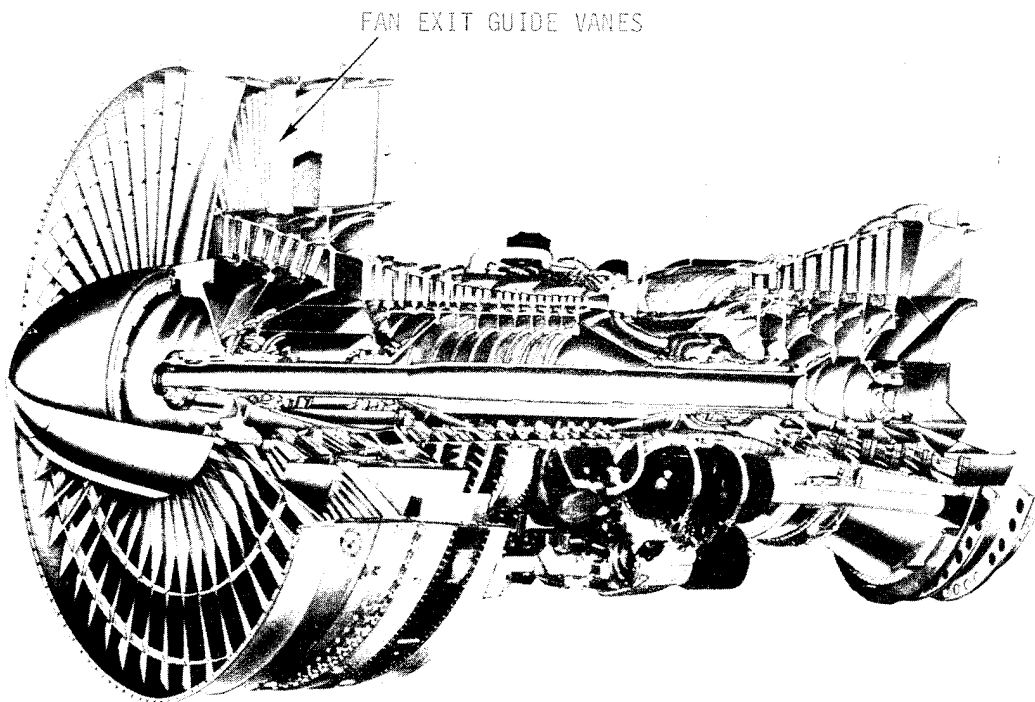


Figure 3-1 JT9D Turbofan Engine

3.1.2 Stress and Vibration Considerations

Vane strength requirements are established by static and dynamic aerodynamic engine stresses. Static stress is primarily due to gas bending loads exerted on the pressure side of the airfoil, whereas dynamic stress is a result of natural frequency vibration of the vane during engine operation. Part design criteria are established which provide sufficient bending and torsional stiffness to avoid excessive vibratory stress in either bending or torsional modes. Early composite vane experience on thin 0.508 mm (0.020 in.) fiber reinforced trailing edge parts (Figure 3-2) during the 1973-1975 period identified the first bending mode as the potential problem vibration mode under selective high flow engine conditions. Occasional part failures initiating from the trailing edge were experienced (Figure 3-3). The primary objective of the design effort under the subject contract was to select vane section size and material/ply configurations which would increase the bending stiffness of the airfoil, provide for more uniform load distribution and thereby decrease first bending mode strain levels primarily at the trailing edge. Another design consideration was to maintain sufficient torsional stiffness to avoid introduction of a first torsion mode which was not previously observed in engine testing. Finally, it was necessary to maintain sufficient vane frequency differences between first bending and torsion to avoid bending-torsion coupling.

3.1.3 Environmental Effects

Two basic environmental factors were of concern in establishing a durable composite fan exit guide vane operating between -12°C (10°F) and 88°C (190°F): long term erosion/corrosion resistance of the vane and the influence of moisture on vane fatigue strength.

Earlier tests, prior to this contract, in both vibration test rigs and engines, have shown that the combination of a 0.25 mm (0.01 in.) thick polyurethane coating over the entire airfoil and a 0.25 mm (0.01 in.) thick leading edge aluminum sheath on the airfoil provide the required erosion/corrosion protection. The polyurethane covered both the aluminum and composite portions of the airfoil.

Concern over the long term durability of non-metallic matrix composite material in the presence of cyclic temperature, load and moisture environment established the need for suitable mechanical property data of "wet" composite material. Both specimens and vanes were exposed to environmental conditions which resulted in moisture levels typical of service operation.

A study was conducted to establish realistic temperature, percent relative humidity and exposure times for composite fan exit guide vanes operating in a service environment. Worst case average temperature and percent relative humidity conditions at airports around the world were established as 24°C (75°F) at 87 percent relative humidity. Vane

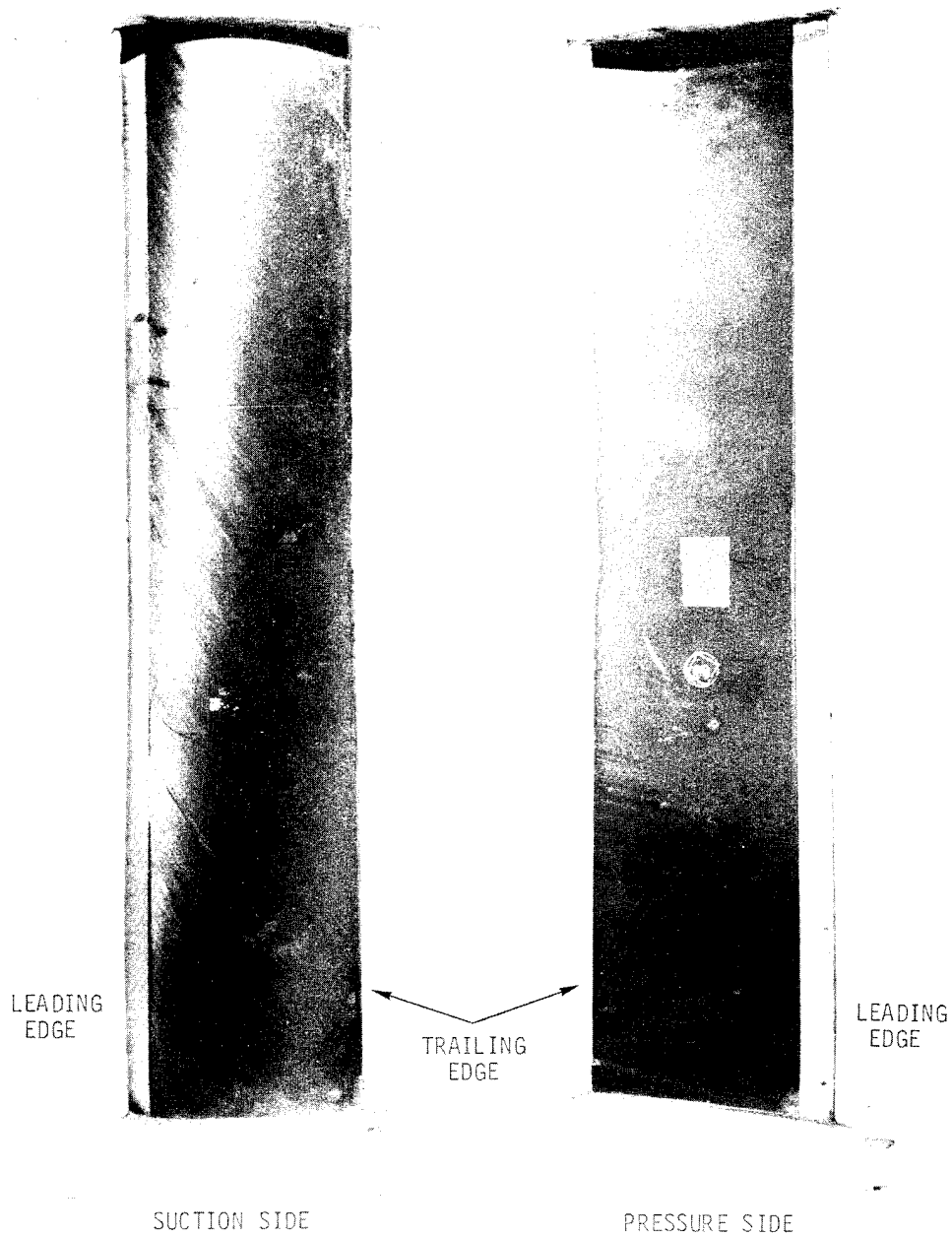


Figure 3-2 Early Design Thin Trailing Edge Graphite/Epoxy Fan Exit Guide Vane After Long Term Endurance Test in Experimental Engine Environment

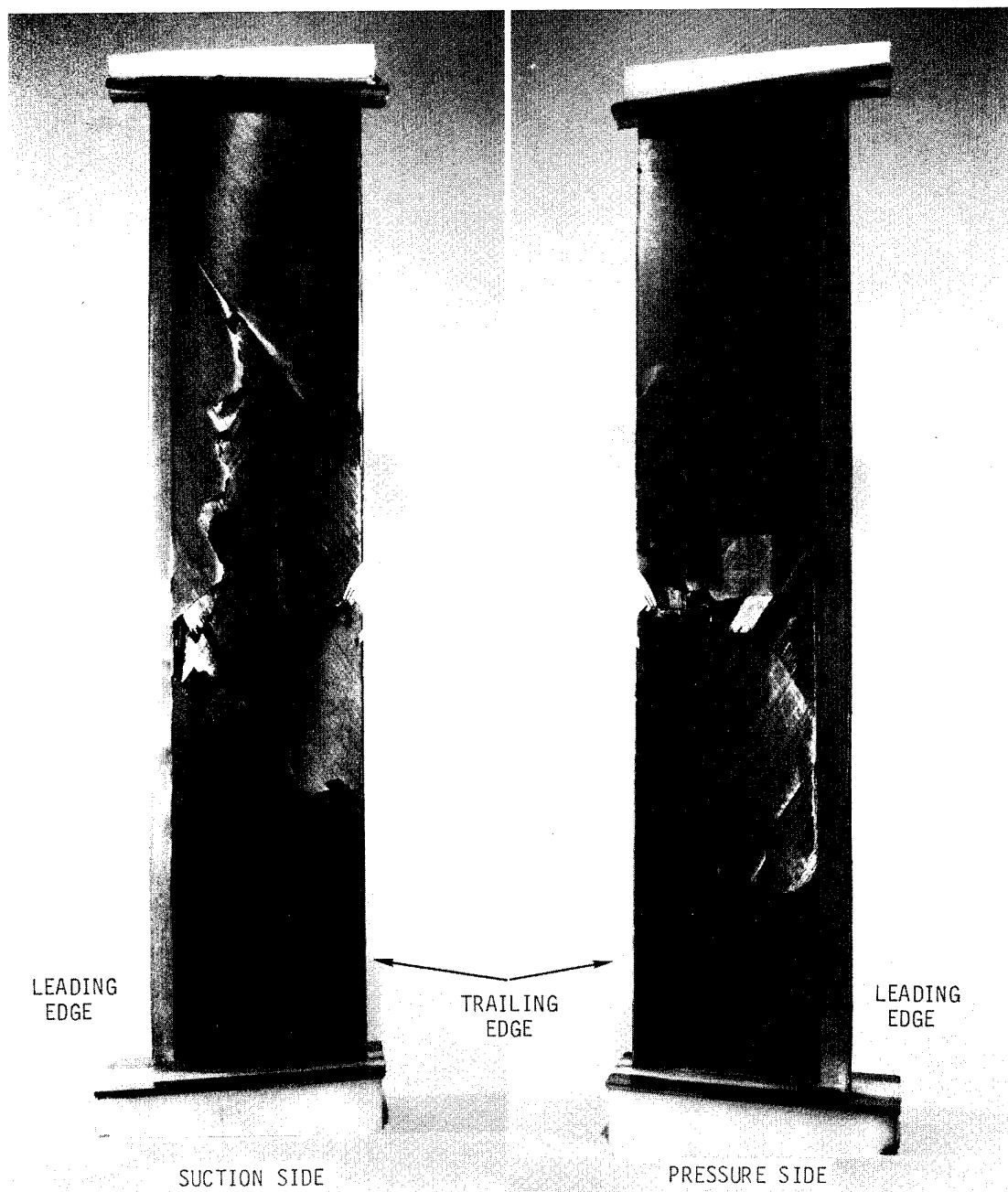


Figure 3-3 Early Design Thin Trailing Edge Graphite/Epoxy Fan Exit Guide Vane Failure After Test in Fatigue Environment

moisture absorption and drying cycles were determined based on service reported data for the lowest JT9D powered aircraft utilization rate during the past seven years reported by one operator. The lowest utilization rate would allow the highest level of moisture to be absorbed by the vane on the ground and would, therefore, present the most conservative approach for determining potential vane property changes. More extensive usage of JT9D powered aircraft during the past several years has substantially increased the utilization factor which has decreased the projected equilibrium concentration of moisture in composite fan exit guide vanes. The lowest utilization time using the conservative approach was determined to be approximately 20 percent flight time. When converted to a daily cycle, this utilization was equivalent to ground exposure for approximately nineteen (19) of every twenty-four (24) hours, and flight drying conditions for the remaining five (5) hours. Typical drying conditions for this five (5) hour period would be approximately 15°C (60°F), zero percent relative humidity at pressures encountered at 10,668 m (35,000 ft.) altitude. A one dimensional computerized analytical diffusion model developed by Springer, Reference 1, was used to determine the required equilibrium moisture content in the 2.03 mm (0.080 in.) thick fiber reinforced trailing edge section of the vane to simulate the projected worst case operating conditions. Moisture content in the trailing edge was considered to be the controlling factor since this airfoil section was most highly stressed. Calculations for a typical graphite/epoxy (3501-6 Hercules resin) system indicated that equilibrium moisture in the 2.03 mm trailing edge section of the vane would be approximately 1.0 weight percent after 18 months of no flight utilization and continuous exposure at 24°C (75°F)/87% relative humidity. However, for the lowest aircraft utilization factor of 20 percent, the equilibrium moisture level in the graphite epoxy vane would be 0.8 weight percent gain achieved in nine months (Figure 3-4). Performing the same analysis for a typical fiberglass system (S glass 7781/5143), the continuous exposure equilibrium moisture content is approximately 1.3 weight percent gain after 18 months. For the 20 percent utilization factor, the equilibrium moisture level drops to 0.9 percent moisture weight gain in 9 months of exposure (Figure 3-5). The rationale for inoculating specimens and vanes with the required moisture content and supporting weight gain data will be presented in section 5.1.3.

The magnitude of fan exit guide vane stress associated with residual fabrication stress, thermal gradients during operation and part volume increase due to moisture absorption was estimated to be small from data presented in Reference 2.

3.1.4 Vane External Geometry and Internal Configuration

Vane external dimensions and shape selected for evaluation in the current program are typical of most fan exit guide vanes found in Pratt & Whitney Aircraft production engines. The part external shape was selected to provide for easy incorporation into existing or advanced models of the JT9D. The airfoil has a 9.1 cm (3.6 in.) chord, and is 43

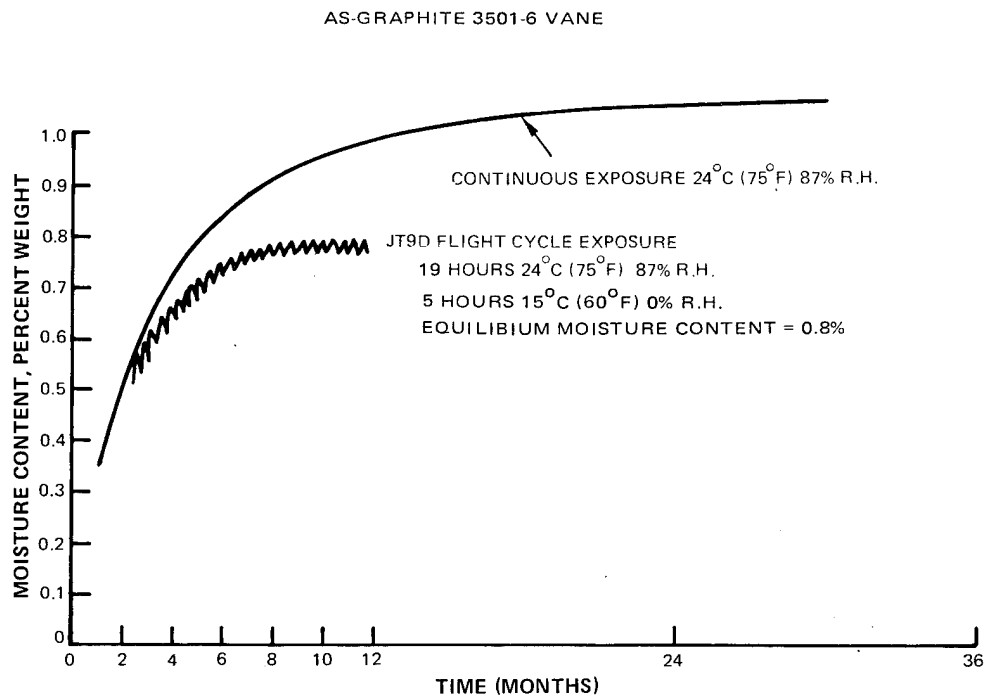


Figure 3-4 Composite Fan Exit Guide Vane Trailing Edge Moisture Content: Trailing Edge Thickness = 2.03 mm (0.080 in.)

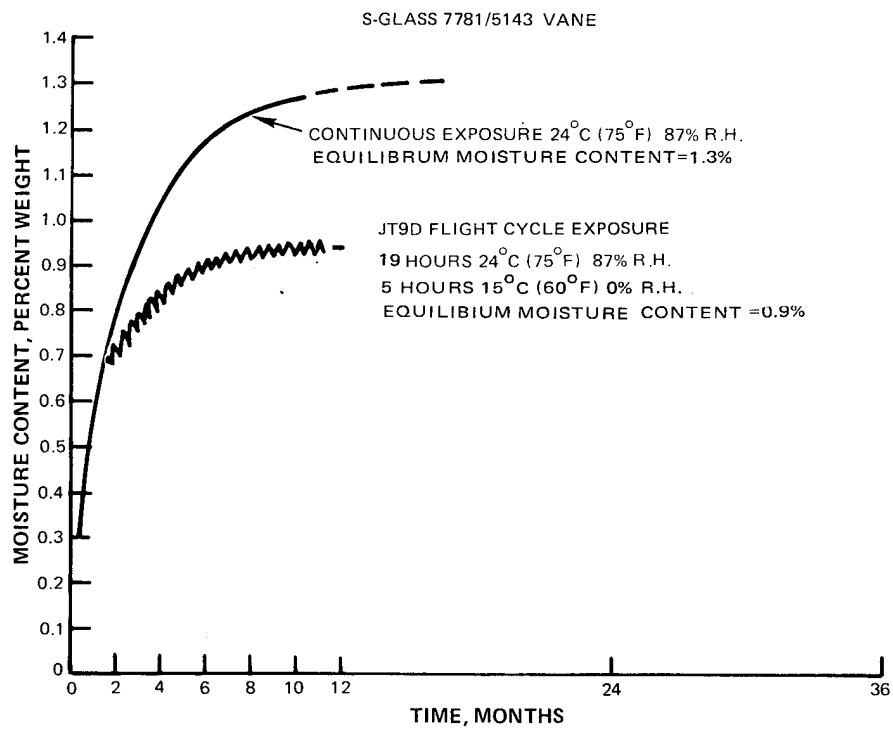


Figure 3-5 Composite Fan Exit Guide Vane Trailing Edge Moisture Content: Trailing Edge Thickness = 2.03 mm (0.080 in.)

cm (17 in.) long. The 9.1 cm chord vane can be assembled into current engine designs with essentially no modification. This design commonality will provide expediency in fabricating, testing and incorporating this light weight, durable, low cost composite airfoil in advanced JT9D engines. The increased thickness trailing edge (Figure 3-6) does result in some predictable aerodynamic performance loss compared to a thin trailing edge part. However, this very small performance loss trades well with the expected weight reduction benefit for a reasonably priced composite vane compared to an aluminum part.

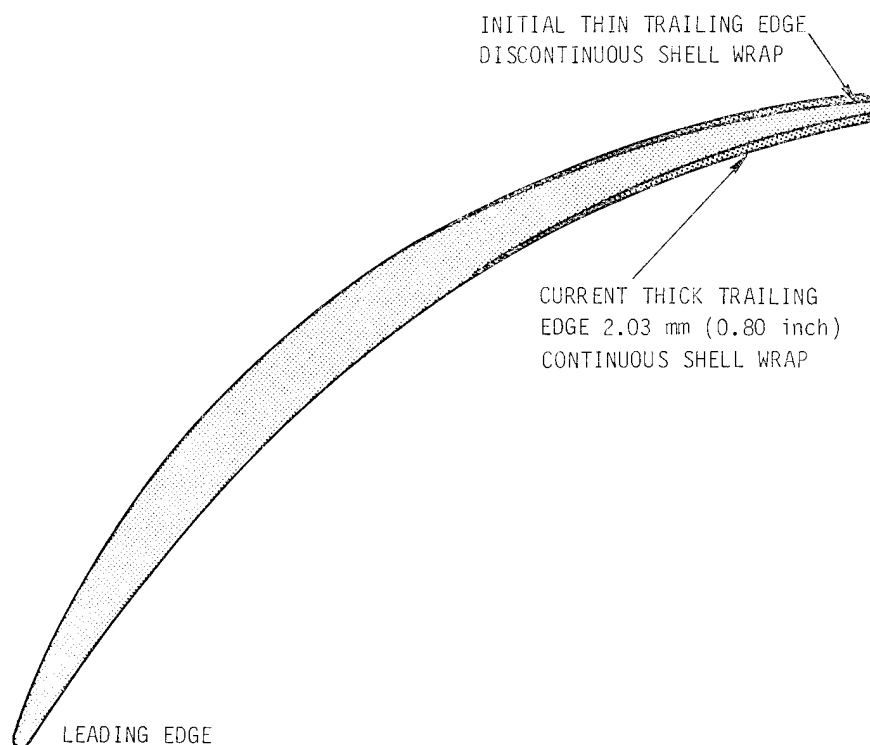


Figure 3-6 Initial and Current JT9D Composite Vane Cross Section

Vane fiber was selected based on four shell materials with different ply orientations evaluated from eight candidate systems. The selection process was aided by engine experience as well as rig high cycle fatigue data obtained during 1973-1975 and NASTRAN finite element analysis prior to the subject contract. A core/shell design was selected with core fibers oriented in the vane span (radial) direction and shell fibers angled to the core. Shell fiber orientation was selected to provide desired torsional stiffness without introducing post-fabrication residual stress cracks. In addition, shell fibers were wrapped around a thicker core trailing edge (Figure 3-7) as compared to an earlier configuration which terminated shell fibers at the thin trail-

ing edge (Figure 3-8). NASTRAN finite element analysis, which will be discussed in more detail in Section 3.2, was used to predict vane static strains, first bending and first torsion frequencies.

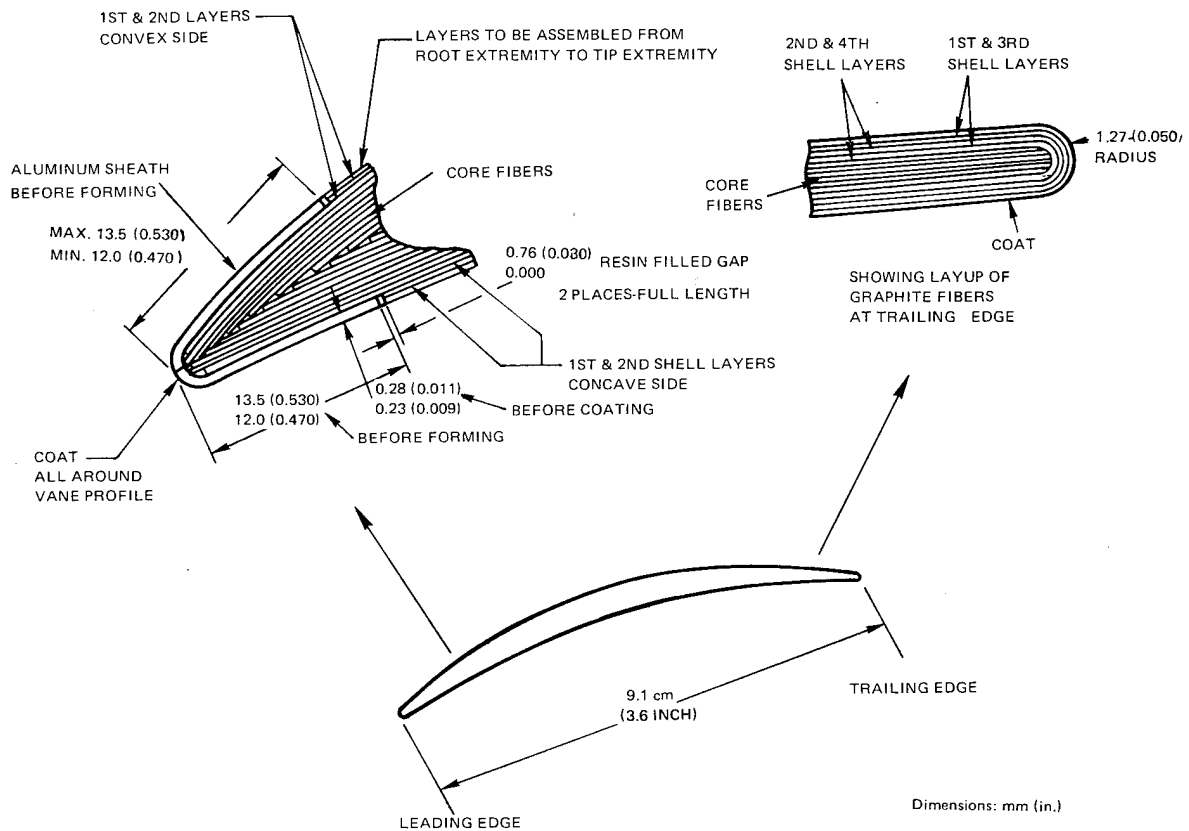


Figure 3-7 Thick Trailing Edge Composite Fan Exit Guide Vane

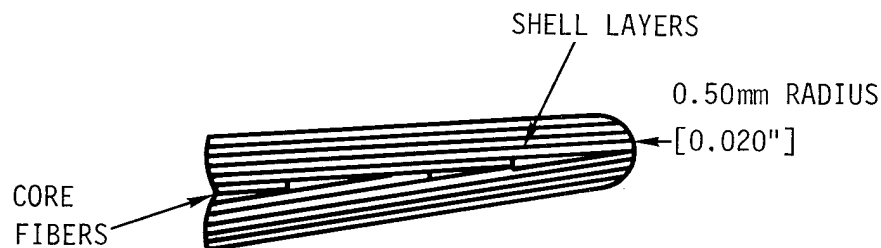


Figure 3-8 Thin Trailing Edge Composite Fan Exit Guide Vane

3.1.5 Fiber and Resin Matrix Material Selection Criteria

Factors influencing the selection of material were: mechanical/physical properties of fiber and resin, material cost, adaptability of the

composite system to low cost processing, material availability and previous fabrication experience of vendors and Pratt & Whitney Aircraft. NASTRAN finite element analyses further refined the selection process by indicating that a typical high modulus 345 GPa (50 msi) core was required for bending stiffness and that shell materials for torsional stiffness could vary in modulus over a wider range. Fiber tensile strength requirements for this stiffness limited part design were met by all candidate fiber materials.

Great Lakes Carbon, Fortafil 5 fiber as it was identified in 1975 met the high modulus requirement (331 GPa (48 msi)) and provided an additional benefit as the lowest cost core fiber available. However, during the 1975 program a fiber quality problem was encountered which resulted in reduced short beam shear strength and poor peel strength. The problem was also visible in high magnification examination of sectioned vanes. These effects are documented in section 4 of the report. To correct these problems Fortafil 5 fiber was subjected to an additional fiber surface treatment which was proprietary to Great Lakes Carbon. Composite test panels fabricated from various batches of fiber, which were surface treated for different periods of time, indicated the desired mix of shear, polyurethane peel and flexure strength was achieved by twice the original fiber treatment time (Figure 3-9). These improved properties resulted in a new fiber specification, Fortafil 5A whose properties were confirmed for each batch of fiber during the contract.

Four shell fiber materials, Fortafil 5A, Hercules AS-2, S-glass fiber S-2 size 449 and S-glass cloth style 6581 were selected to provide a wide range of moduli for torsional properties.

Resin system selection was based on a number of requirements. The minimum wet glass transition temperature, T_g , of the resin must be higher than the maximum operating temperature of the vane. Low moisture weight gain of the resin system was required. Selected resins should be similar to resins currently being flight tested in commercial and military aircraft under NASA and Department of Defense sponsorship. Moderate ductility up to 1.5 percent, low cost and commercial availability of the raw materials were further requirements. Previous resin selection at Pratt & Whitney Aircraft in the earlier vane program evaluated Hercules 3501 resin and a proprietary system formulated by Composites Horizons, then known as Structural Composites, Inc. (SCI). The two vane fabricators selected for the subject program, TRW and Composites Horizons, individually selected their resin systems to meet the above requirements. Composites Horizons selected the same proprietary resin, identified as CH 4010, which was used in the earlier program and was compatible with their core pultrusion and shell ply prepreg procedures. TRW selected a commercially available mix of DEN 438, DER 331 and TONOX 60/40 which would be compatible with either ply prepregging or pultrusion.

60 v/o GR/EPON 826 RESIN SPECIMENS
DATA FROM 1975 PERIOD

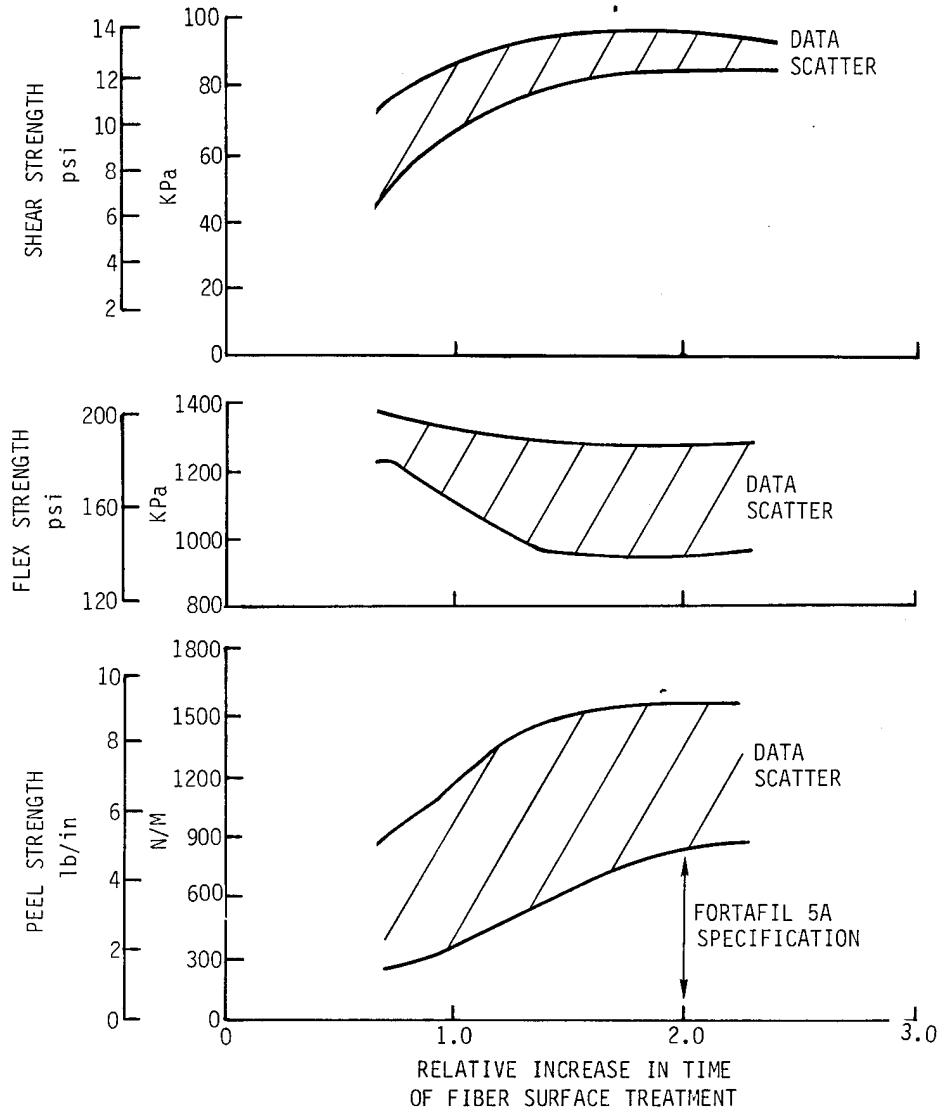


Figure 3-9 Composite Shear, Flexural and Polyurethane Peel Strength of Fortafil 5A Composites vs. Relative Degree of Fiber Surface Treatment

3.2 VANE ANALYSES

3.2.1 Preliminary Screening of Vane Candidates

Eight different thick trailing edge vane configurations with varying shell material/ply orientation combinations were evaluated using

NASTRAN finite element analysis (Table 3-I). Comparisons were made to thin trailing edge aluminum vanes and to thin trailing edge composite vanes, which had been engine tested during the 1973-1975 period. The candidates were evaluated for bending and torsional stiffness and frequency as well as strain at the trailing edge of the vane. The aluminum vane, which has been successfully operated in JT9D engines, was used as a baseline to establish target properties. Particular attention was given to reduce radial strain at the trailing edge. It was this area of the airfoil which experienced the most distress in earlier programs.

Candidates 5, 6 and 8 were eliminated for high static strain at the trailing edge. Furthermore, the poor compressive strength characteristics of Kevlar in candidate vane number 5 would not be desirable since the vane trailing edge section experienced compressive loading during flutter excitation. Vane configuration 7 was not considered due to relatively high static strain at vane maximum thickness and vane 4 was eliminated in preference to a modification of vane 2 containing a glass cloth shell/345 GPa (50 M) modulus graphite core configuration. As a result of these analyses, four candidates, presented in Table 3-II, were selected for detailed design, fabrication, test and evaluation. Slight changes to shell ply fiber orientation were permitted to minimize fabrication residual stresses without significantly changing the critical vane property requirements. Composites Horizons selected +35-35-35+35 degrees for four ply graphite shell construction, whereas TRW selected +30 degrees. Both S-glass shell configurations use two plies with +45 fiber orientation.

3.2.2 Characteristics of Four Selected Vane Candidates

All four vane candidates contained a high modulus core to meet bending stiffness (K_B) requirements. High bending stiffness reduced the potential for excessive vibratory stress during engine operation. Torsional stiffness (K_T) was a second order concern in the design of the fan exit guide vane. No vibratory response in torsion had been observed in either rig or engine tests. However, adequate torsional stiffness is required so as not to compromise torsional frequency. In addition, the margin between bending and torsional frequency should be maintained to minimize the possibility of mode coupling. First bending and torsion stiffness properties for the four candidate thick trailing edge vanes were compared to the earlier thin trailing edge vane (Figure 3-10, 3-11). These data were obtained using NASTRAN finite element analysis with elemental properties determined by classical laminate theory. Bending spring rates were higher for the four candidate vanes, whereas torsional spring rates decreased. In addition to stiffness, a comparison was made between experimental first bending and first torsion frequency test data for the thin trailing edge vane and NASTRAN dynamic analysis data for the thick trailing edge vane. The differences between bending and torsion frequencies are considered sufficient to avoid mode coupling during vane excitation (Figure 3-12). However, the bending to torsion frequency difference for the two fiberglass shell vane configurations is smaller than encountered in previous programs.

TABLE 3-I

NASTRAN CALCULATED PROPERTIES OF CANDIDATE FAN EXIT GUIDE VANES

CONFIGURATION	K _B MN/M (lbs/in)	K _T M-N/deg (in-lbs/deg)	E ₁₁ GPa (msi)	G ₁₂ GPa (msi)	f _B Hz	f _T Hz	Radial Static Strain ε ^x Max. Thickness % Strain	Strain ε ^x Trailing Edge % Strain
10.2 cm (4") Chord								
Aluminum	0.219	3.81	73.1	26.2	162	397	0.0887	-0.1528
Thin Trailing Edge	(1251)	(33.7)	(10.6)	(3.8)				
9.1 cm (3.6") Chord								
Original Thin TE Configuration	0.241	3.29	135.1	19.0	220	565	0.1000	-0.2800
345 GPa (50 M) Graphite 0° Core	(1374)	(29.1)	(19.6)	(2.75)				
345 GPa (50 M) Graphite 4-Ply								
+35° Shell								
Candidate Thick TE Configurations								
1. 345 GPa (50 M) Graphite 0° Core	0.339	2.68	142.7	15.5	248	531	0.0847	-0.1720
345 GPa (50 M) Graphite 4-Ply	(1936)	(23.7)	(20.7)	(2.24)				
+35° Shell								
2. 345 GPa (50 M) Graphite 0° Core	0.286	1.38	127.6	7.9	227	393	0.0945	-0.1990
S-Glass 4-Ply +45° Shell	(1634)	(12.2)	(18.5)	(1.15)				
3. 345 GPa (50 M) Graphite 0° Core	0.307	1.91	134.5	11.03	239	465	0.0910	-0.1740
207 GPa (30 M) Graphite 4-Ply	(1750)	(16.9)	(19.5)	(1.60)				
+35° Shell								
4. 207 GPa (30 M) Graphite 0° Core	0.281	2.7	143.4	15.6	230	527	0.1100	-0.2042
345 GPa (50 M) Graphite 7-Ply	(1607)	(23.9)	(20.8)	(2.26)				
+45°, 0°, -45° Shell								
5. Kevlar 0° Core	0.246	2.7	84.8	15.6	230	541	0.1260	-0.2330
345 GPa (50 M) Graphite 7-Ply	(1407)	(23.9)	(12.3)	(2.26)				
+45°, 0°, -45° Shell								
6. Syntactic Foam Core	0.176	2.52	50.5	14.5	177	522	0.2067	-0.2900
345 GPa (50 M) Graphite 7-Ply	(1004)	(22.3)	(7.32)	(2.11)				
+45°, 0°, -45° Shell								
7. Syntactic Foam Core	0.247	2.96	75.2	17.1	216	566	0.1588	-0.2050
345 GPa (50 M) Graphite 11-Ply	(1408)	(26.2)	(10.9)	(2.48)				
+45°, 0°, -45° Shell								
8. 207 GPa (30 M) Graphite Core	0.217	1.71	91.1	9.7	198	424	0.1326	-0.2700
207 GPa (30 M) Graphite 4-Ply	(1238)	(15.1)	(13.2)	(1.40)				
+35° Shell								

¹Frequency data based on beam theory using bulk vane modulus properties

TABLE 3-II

SELECTED FAN EXIT GUIDE VANE CONFIGURATIONS AND PROCESSES

Core			Shell		
Fiber Modulus GPa (msi)	Orien- tation, Degrees	Material	Fiber Modulus GPa (msi)	Orienta- tion, Degrees	
<u>Pultrusion and Compression Molding</u>					
Portafil 5A	331 (48)	0	Portafil 5A	331 (48)	+35, -35, -35, +35
Graphite			Graphite Plies		
Portafil 5A	331 (48)	0	S-Glass Cloth	41 (6.0)	+45, -45
Graphite			Style 6581		
<u>Ply Lay-up and Compression Molding</u>					
Portafil 5A	331 (48)	0	AS-2 Graphite Plies	221 (32)	+30, -30, +30, -30
Graphite					
Portafil 5A	331 (48)	0	Owens Corning	83 (12.0)	+45, -45
Graphite			S-2 Glass Roving		
			449 Size		

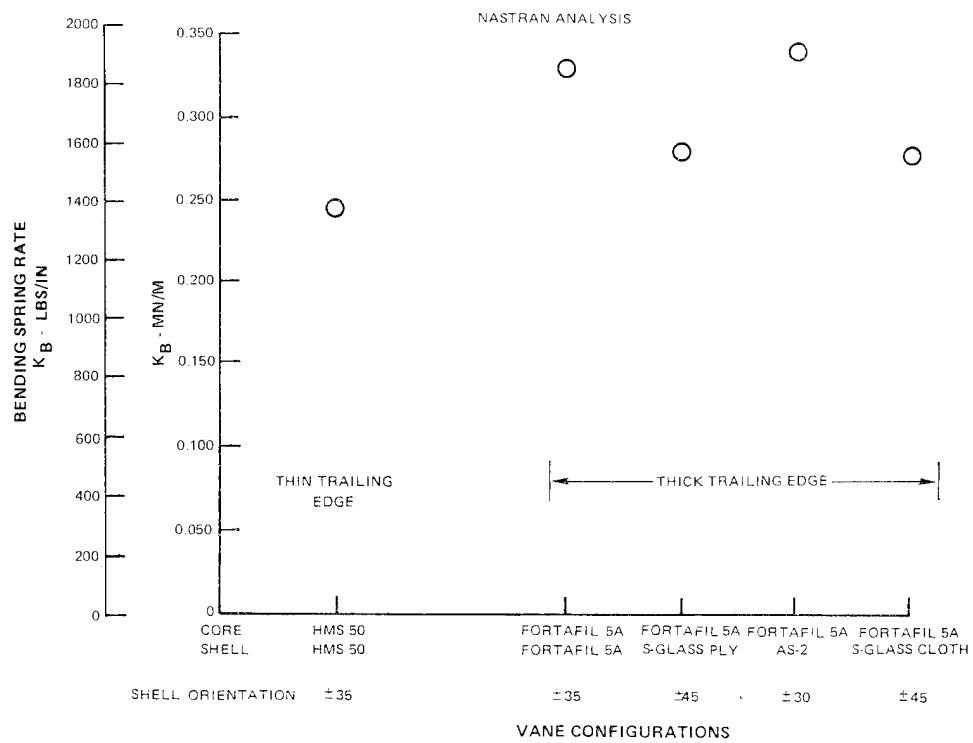


Figure 3-10 Composite Fan Exit Guide Vane Bending Stiffness

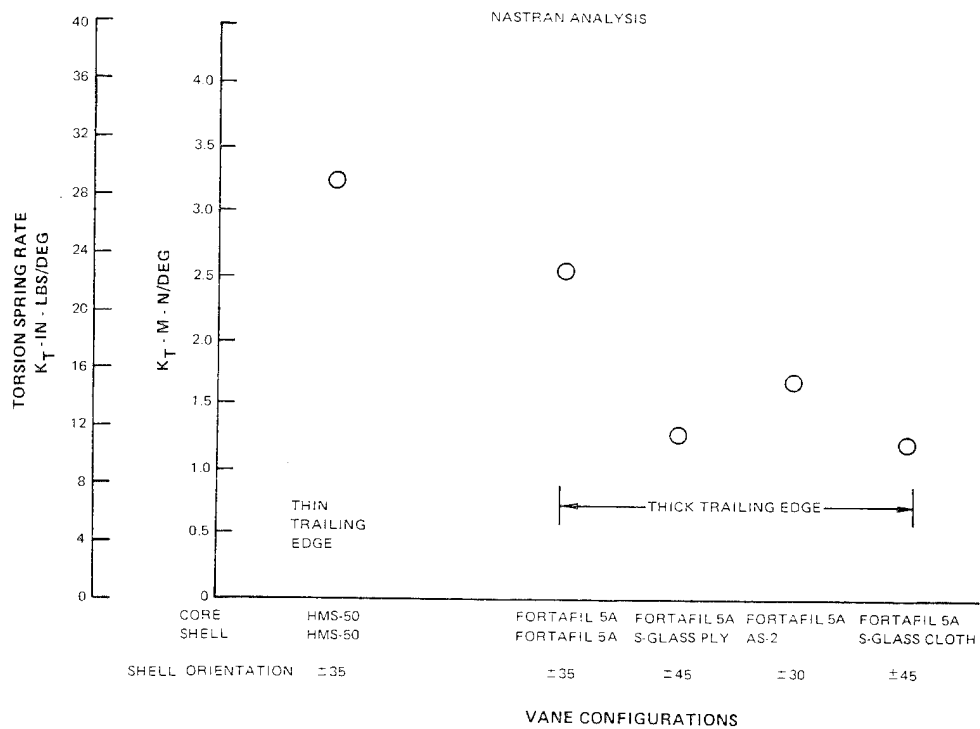


Figure 3-11 Composite Fan Exit Guide Vane Torsional Stiffness

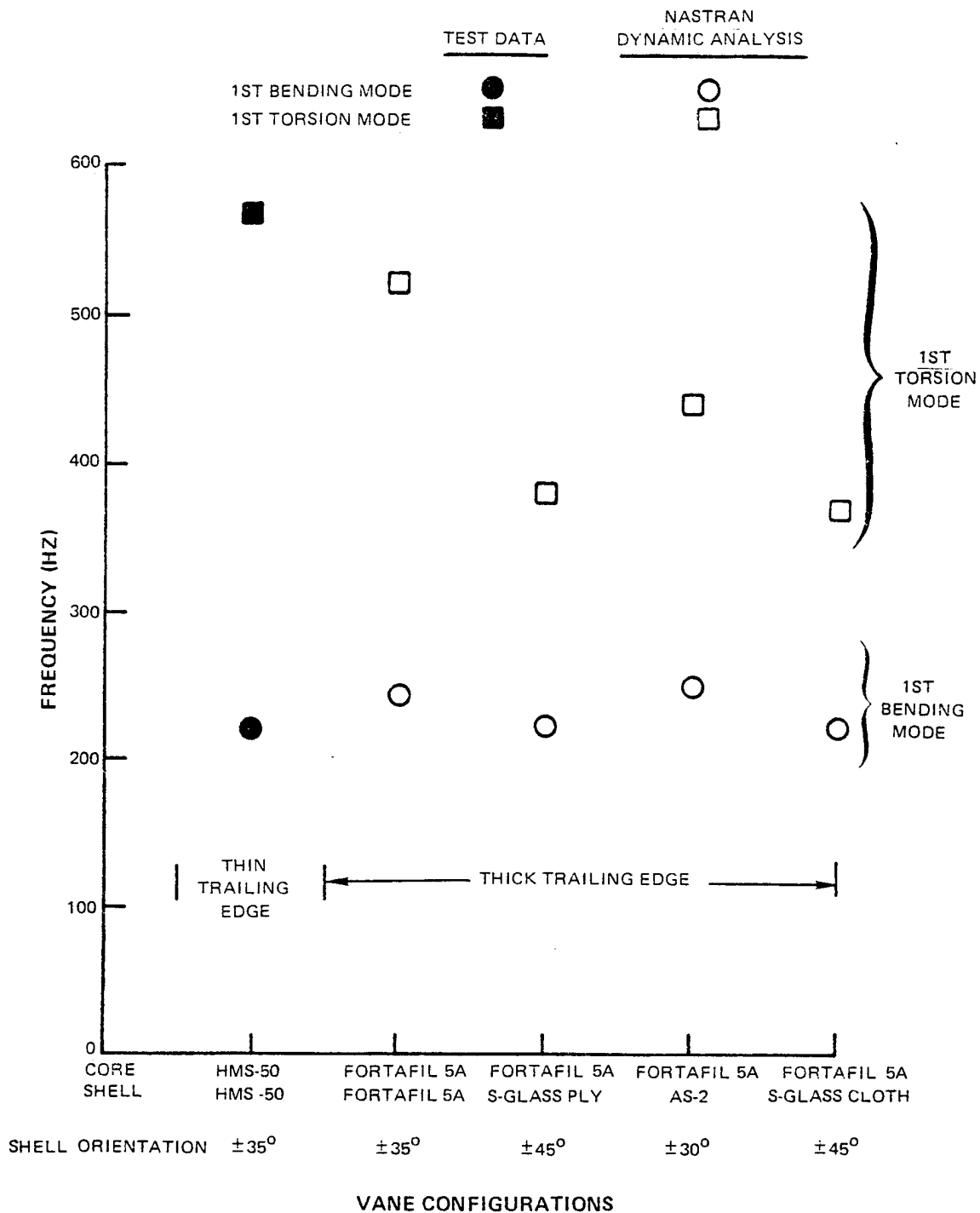


Figure 3-12 Composite Fan Exit Guide Vane Torsion and Bending Frequency

Chordwise distribution of radial strain was compared for both thick and thin trailing edge vanes of comparable material/ply orientation for maximum static load on the airfoil at the vane midspan (Figure 3-13). A thickening of the airfoil, starting at midchord and gradually continuing to the trailing edge, provided additional high modulus core fiber which decreased the average strain in the core from the 6.4 cm (2.5 in.) chord location to the trailing edge. The use of the trailing edge shell wrap-around concept in conjunction with the thick trailing edge permitted unidirectional core to move approximately 7.62 mm (0.30 in.) closer to the trailing edge outer surface which also contributed to increased bending stiffness. These additive effects of increasing core thickness and moving the core closer to the trailing edge resulted in decreased strain from $-2800 \mu\epsilon$ to $-1720 \mu\epsilon$. Furthermore, the wrap around shell concept was expected to provide a two-fold benefit. One of these benefits was expected to be improved fiber/resin homogeneity which would reduce peak strains at the trailing edge. Another benefit expected was an improved shear tie in the shell around the trailing edge radius from the concave side of the airfoil to the convex side. The earlier vane was designed with concave and convex shell fibers terminating at the trailing edge.

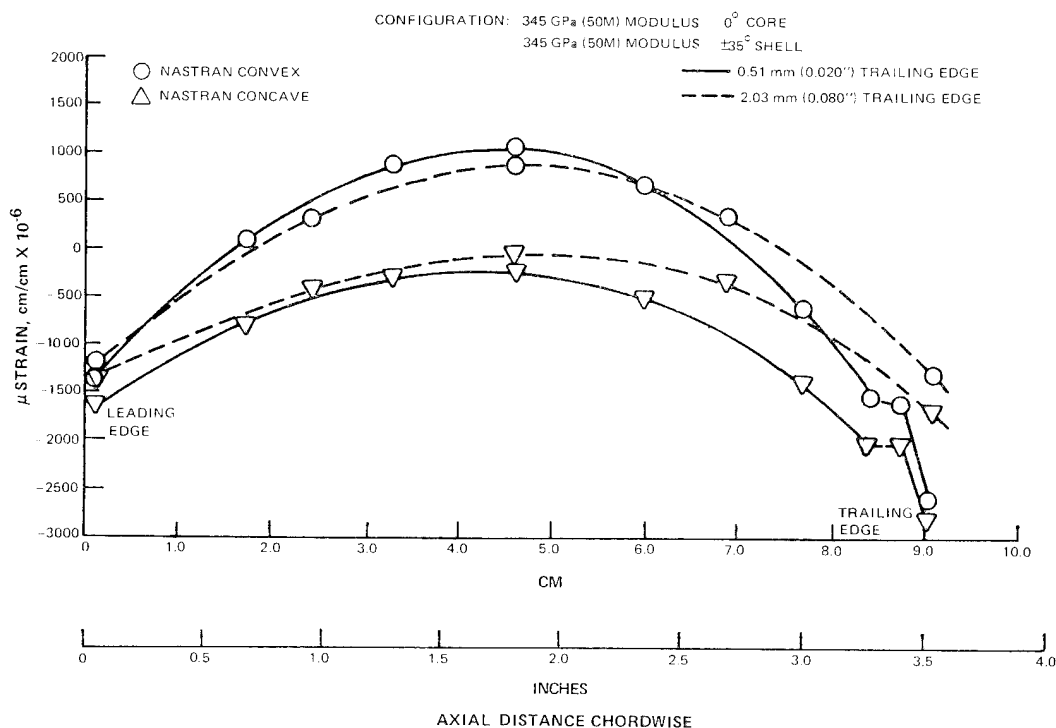


Figure 3-13 Composite Fan Exit Guide Vane Strain Distribution
NASTRAN Static Pressure Load Analysis, 34 KPa (5 psi)

3.2.3 Stress and Vibration NASTRAN Analysis

Prediction of the strain distribution of each of the four vane designs in a typical high bypass ratio engine environment was accomplished through use of a static and dynamic finite element NASTRAN analysis and substantiated by bench test data. The modeling techniques used in the NASTRAN analysis have been calibrated to static bladder load testing (Section 5.1.2) of the original thin trailing edge composite vane design. A dynamic analysis was also performed on each concept to accurately determine natural frequency and mode shape. This information was compared to shaker table strain gage results for further calibration of the NASTRAN model, allowing accurate prediction of the engine stress strain condition for each vane design.

The NASTRAN element used in the analysis is a 2D compatible bending membrane element in 3D space (Clough element). The model breakup consisted of 48 elements along the vane chord and 20 stations spanwise along the 43 cm (17 in.) vane span (Figures 3-14, 3-15), making a total of 960 elements. The individual element properties are generated by a pre-processor which calculates membrane, bending and in-plane shear properties based on the ply lay-ups in the area. These calculations are based on classical laminate theory presented in Reference 3.

Mechanical property data obtained in the subject program at 60 \pm 5 percent volume composite fiber and reported in Section 4 as well as properties extracted from Reference 4 were used as input to the NASTRAN analyses. A summary of these data is presented in Table 3-III. Results of static and dynamic NASTRAN analyses are presented in Table 3-IV and represents a second calculated iteration for materials selected in the subject program. The most significant change from previous calculations reported in Table 3-I was an increase of approximately 10 percent in radial strain (ϵ^x) at the trailing edge as a result of lower values of composite modulus. The chordwise distribution of radial static strain for both convex and concave surfaces of the airfoil for three of the four configurations are shown in Figures 3-16, 3-17 and 3-18. The strain distribution is quite similar for graphite vanes. However the glass shelled vane showed an increase in trailing edge radial strain of approximately 20 percent. The glass cloth shell vane showed similar strain distribution to glass fiber shell vane.

Chordwise distribution of chordwise strain was also determined for three of the four vane configurations and is presented in Figures 3-19, 3-20, and 3-21. Peak chordwise strain at the trailing edge for both graphite vane designs was higher than strain on the fiberglass shell vane. Furthermore, the chordwise strain on the fiberglass shell vane was more uniform towards the trailing edge of the airfoil, indicating there might be competitive regions for failure away from the trailing edge. These analytically determined comparisons were later substantiated by strain gage test data (Section 5), and showed different modes of failure attributable to varying strain patterns.

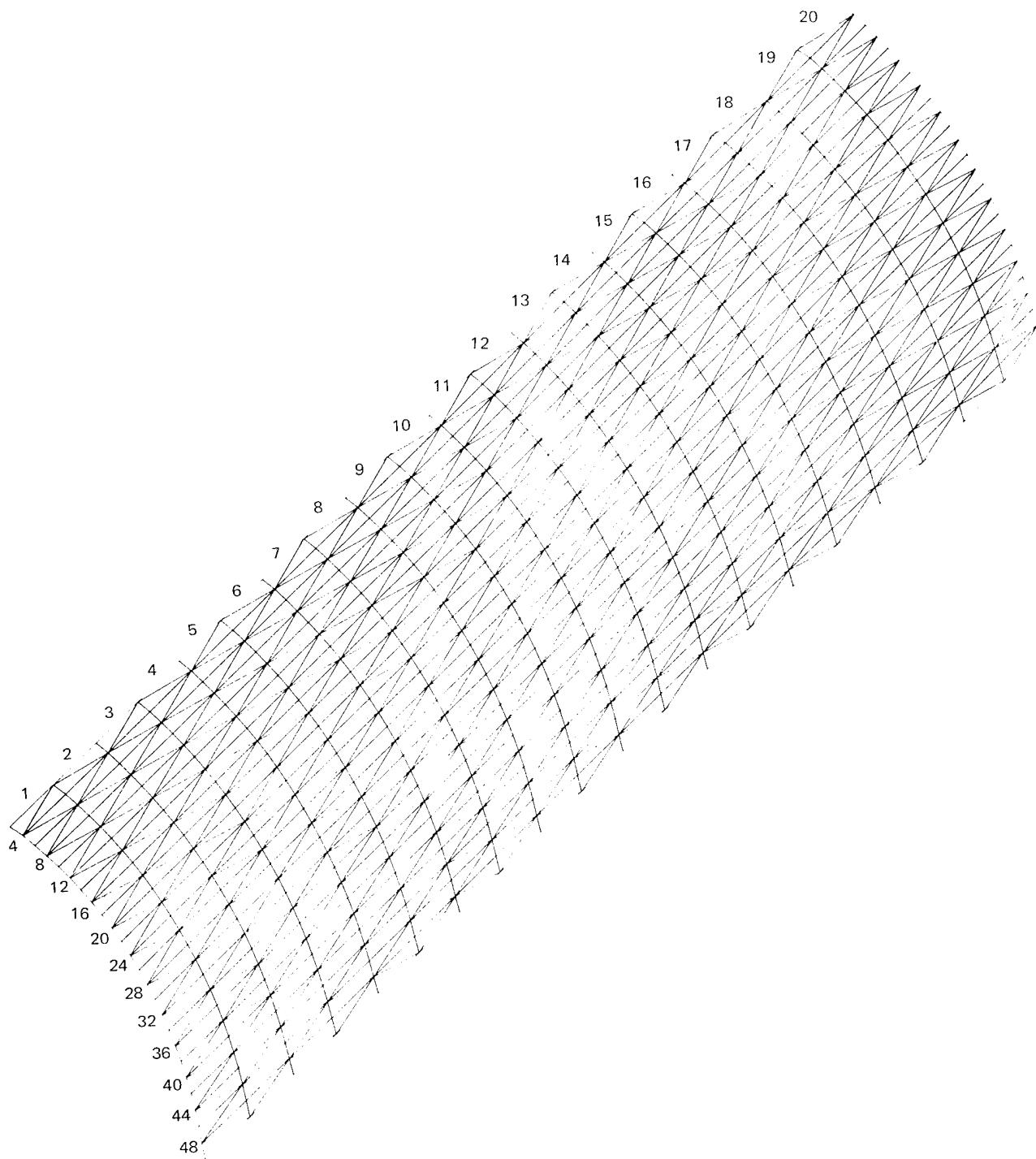


Figure 3-14 Fan Exit Guide Vane View of NASTRAN Plate Elements - 48
Chordal Sections, 20 Spanwise Sections for Core and
Shell

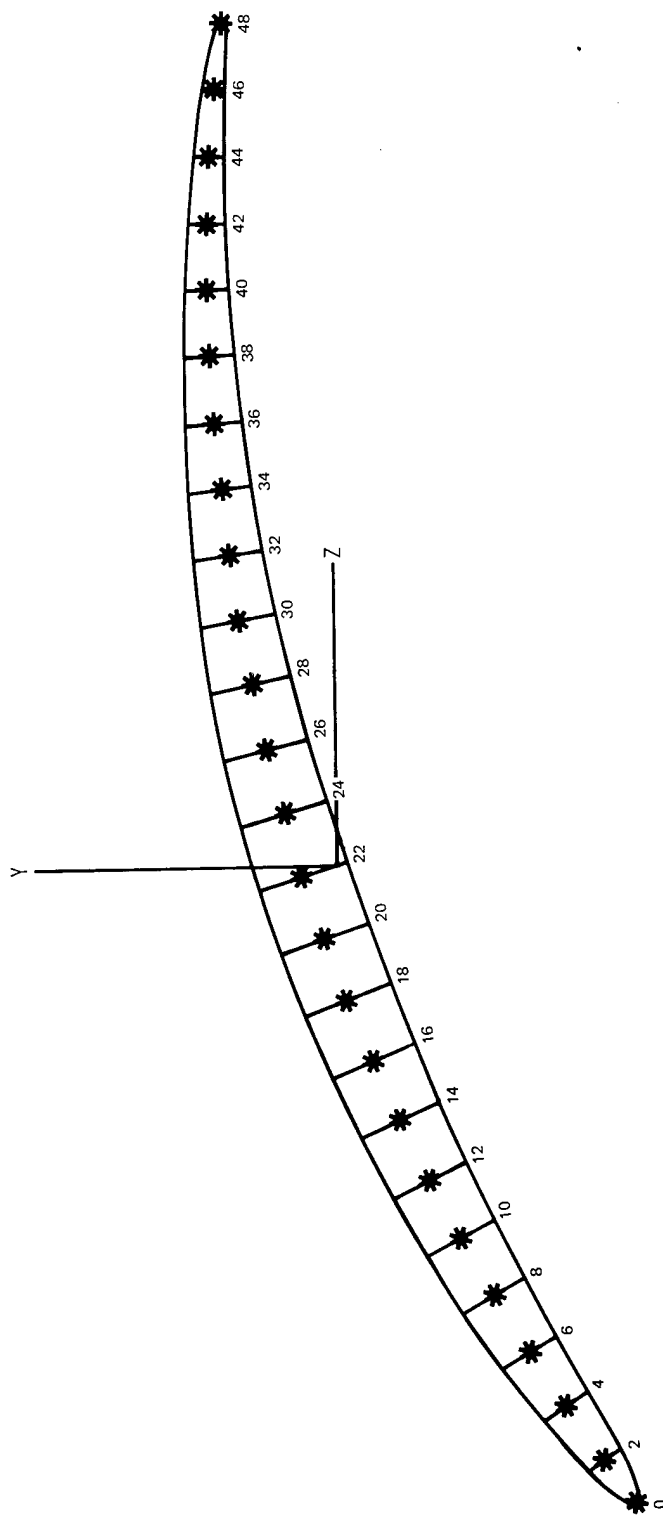


Figure 3-15 Fan Exit Guide Vane Airfoil Cross Section for NASTRAN Analysis at 15% Span - 48 Chordal Plate Elements for Core and Shell

TABLE 3-III

UNIDIRECTIONAL PROPERTIES OF CORE AND SHELL COMPOSITE MATERIALS
60 PERCENT FIBER VOLUME

	Longitudinal Modulus GPa (msi)	Transverse Modulus GPa (msi)	Poisson's Ratio (γ)	Shear Modulus GPa (msi)	Density gm/cc (lb/in ³)
Fortafil 5A Graphite	147.6 (21.4)	11.7 (1.7)	0.30	4.48 (.65)	1.50 (0.054)
AS-2 Graphite	136.5 (19.8)	11.7 (1.7)	0.21	4.48 (.65)	1.50 (0.054)
S-Glass Tape	51.7 (7.5)	15.5 (2.2)	0.25	7.58 (1.10)	1.91 (0.069)
S-Glass Cloth	31.0 (4.5)	31.0 (4.5)	0.25	7.58 (1.10)	1.91 (0.069)

Note: Properties obtained from subject test program and from Reference 3

TABLE 3-IV

NASTRAN CALCULATED PROPERTIES OF THICK TRAILING EDGE FAN EXIT GUIDE VANES

	K_B	K_T	E_{11}	G_{12}	f_B	f_T	Radial Static Strain ϵ^N	
	MN/M (lbs/in)	M-N/Deg (in-lb/deg)	GPa (msi)	GPa (msi)	Hz	Hz	Max Thickness % Strain	Trailing Edge % Strain
Fortafil 5A 0° Core/ Fortafil 5A +35° Shell	0.330 (1885)	2.65 (23.4)	137.2 (19.9)	14.8 (2.15)	244	535	0.0955	-0.1910
Fortafil 5A 0° Core/ AS-2 +30° Shell	0.320 (1825)	1.82 (16.1)	146.9 (21.3)	10.0 (1.45)	240	468	0.0985	-0.1980
Fortafil 5A 0° Core/ S-Glass Fiber +45° Shell	0.276 (1575)	1.29 (11.4)	122.0 (17.7)	7.4 (1.07)	220	382	0.1100	-0.2285
Fortafil 5A Core/ S-Glass Cloth +45° Shell	0.275 (1570)	1.20 (10.6)	121.4 (17.6)	7.0 (1.02)	220	368	0.1095	-0.2295

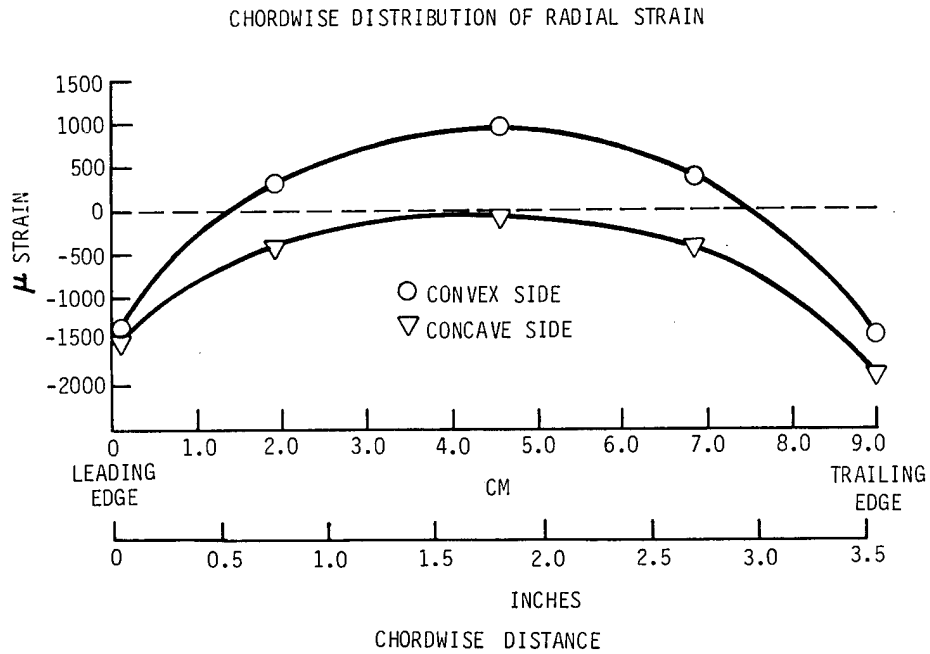


Figure 3-16 Fortafil 5A Core and +35° Shell Composite Fan Exit Guide Vane - NASTRAN Static Pressure Load Analysis 34 KPa (5 psi)

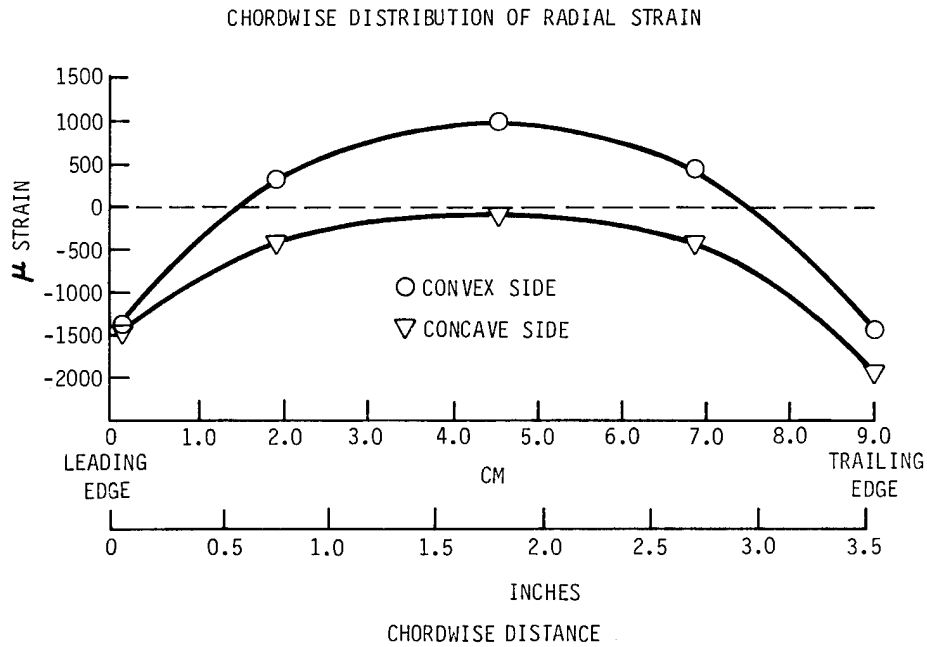


Figure 3-17 Fortafil 5A Core and +30° AS-2 Shell Composite Fan Exit Guide Vane - NASTRAN Static Pressure Load Analysis, 34 KPa (5 psi)

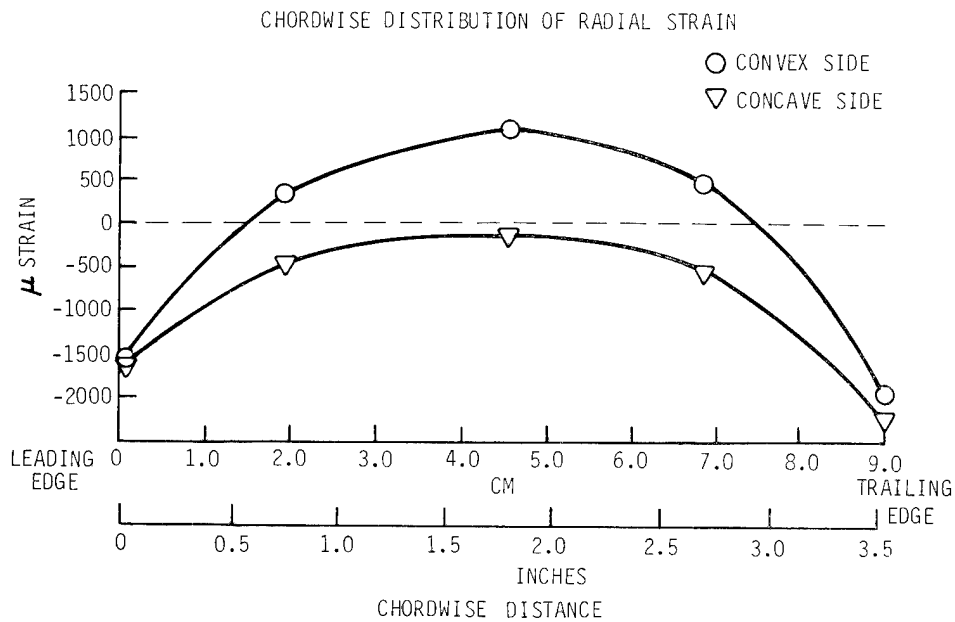


Figure 3-18 Fortafil 5A Core and +45° Glass Fiber Shell Composite Fan Exit Guide Vane - NASTRAN Static Pressure Load Analysis, 34 KPa (5 psi)

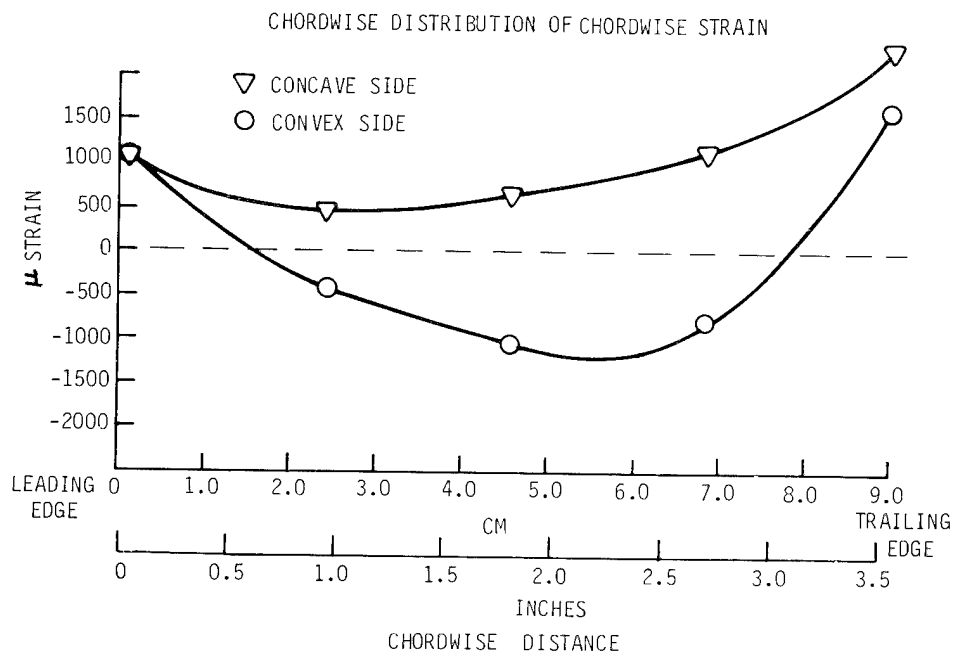


Figure 3-19 Fortafil 5A Core and +35° Shell Composite Fan Exit Guide Vane - NASTRAN Static Pressure Load Analysis, 34 KPa (5 psi)

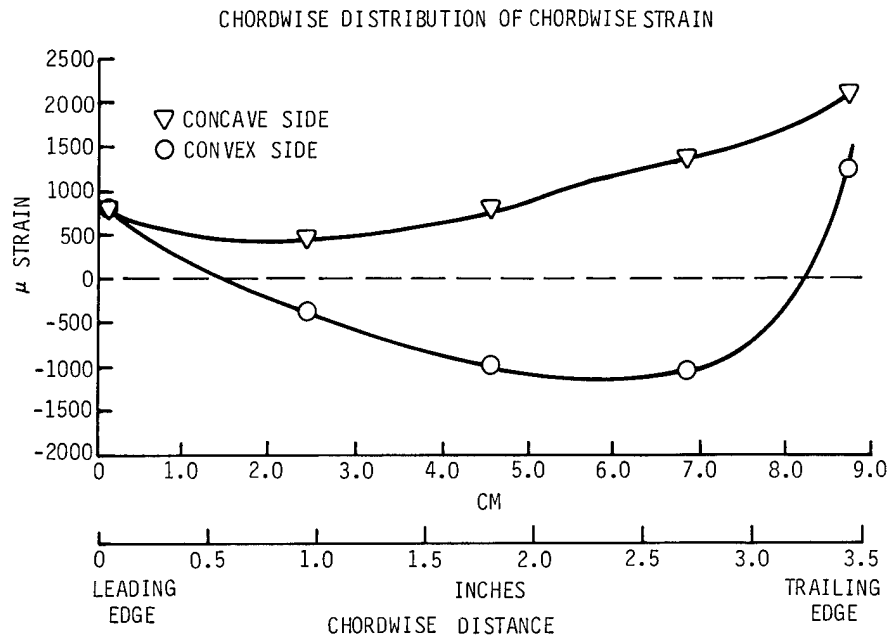


Figure 3-20 Fortafil 5A Core $+30^\circ$ AS-2 shell Composite Fan Exit Guide Vane - NASTRAN Static Pressure Load Analysis, 34 KPa (5 psi)

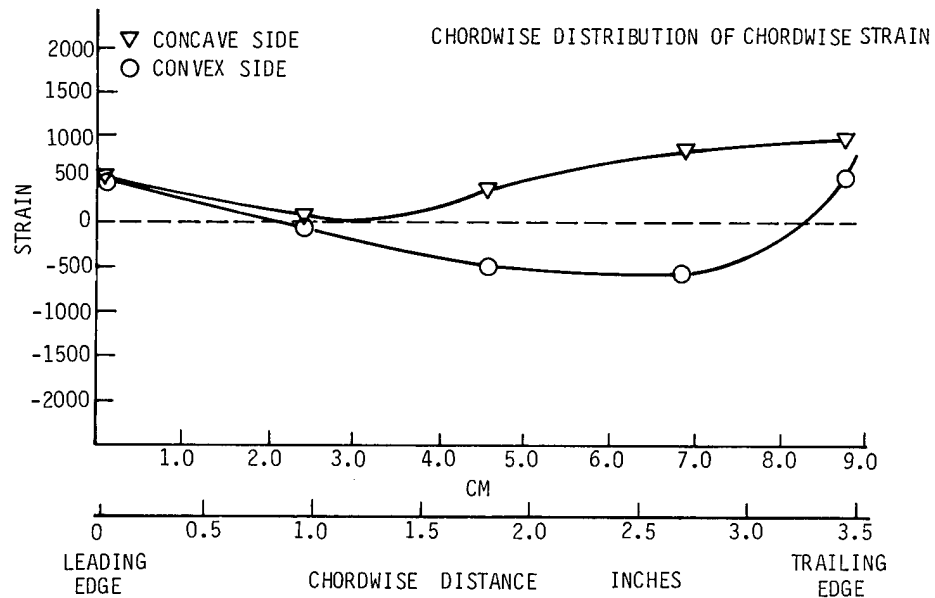


Figure 3-21 Fortafil 5A Core and $+45^\circ$ S-Glass Fiber Shell Composite Fan Exit Guide Vane - NASTRAN Static Pressure Load Analysis, 34 KPa (5 psi)

4.0 MATERIALS EVALUATION AND VANE FABRICATION

4.1 MATERIALS EVALUATION

4.1.1 Background

During the mid 70's, mechanical strength deficiencies were noted in various graphite composite fan exit guide vanes which were attributed to contaminated fiber. These material deficiencies also resulted in compromised part durability. As a result of this problem, several mechanical property measurements were emphasized in the materials control test plan for the subject program. Those properties obtained in the program were flexure strength, short beam shear strength, flexure modulus and polyurethane to composite panel peel strength. The effects of moisture and temperature on these panel properties were evaluated and comparisons were made to data of specimens removed from vanes. Some of the data presented herein are a compilation of precontract 1975 information generated by Great Lakes Carbon, Composites Horizons and Pratt & Whitney Aircraft and will be identified accordingly.

4.1.2 Composite Mechanical Properties

During the 1975 program, a mechanical property correlation for panels fabricated with Fortafil 5 was found to exist between shear, flexure and polyurethane to composite peel strength. To achieve the best balance of all three properties and eliminate the fiber contamination problem, various fiber surface treatments were undertaken by Great Lakes Carbon. The results of those treatments indicated that significant improvements in shear strength and polyurethane peel strength were obtained when panels were fabricated from fiber which had twice the level of surface treatment previously received. This fiber surface conditioning which is proprietary to Great Lakes Carbon was agreed upon by all parties and the modified fiber was identified as Fortafil 5A and used in the subject program. The failure characteristics of low peel strength showed fiber pullout from the composite rather than adhesive failure between the composite and polyurethane film. Peel strength was also a good indication of proper polyurethane bonding conditions to the composite part. A typical example of the result of contaminated fiber on vane microstructure can be seen in Figure 4-1. Also apparent are resin rich areas at the vane trailing edge.

Material acceptance data were obtained for all of the fiber, cloth and resin materials used to fabricate vanes. Critical mechanical and physical properties of four separate batches of Great Lakes Carbon Fortafil 5A showed excellent data repeatability when tested by the fiber manufacturer (Table 4-I). In addition to strength and modulus properties, the peel strength of 0.254 mm (0.010 in.) polyurethane film bonded to composite panels was established. Peel tests on flat specimens indicated no excessive fiber pullout and good bonding of the polyurethane to the epoxy novalac of the composite panel. This added peel requirement was established to confirm that "clean" fiber surfaces were being used for specimen and vane fabrication.

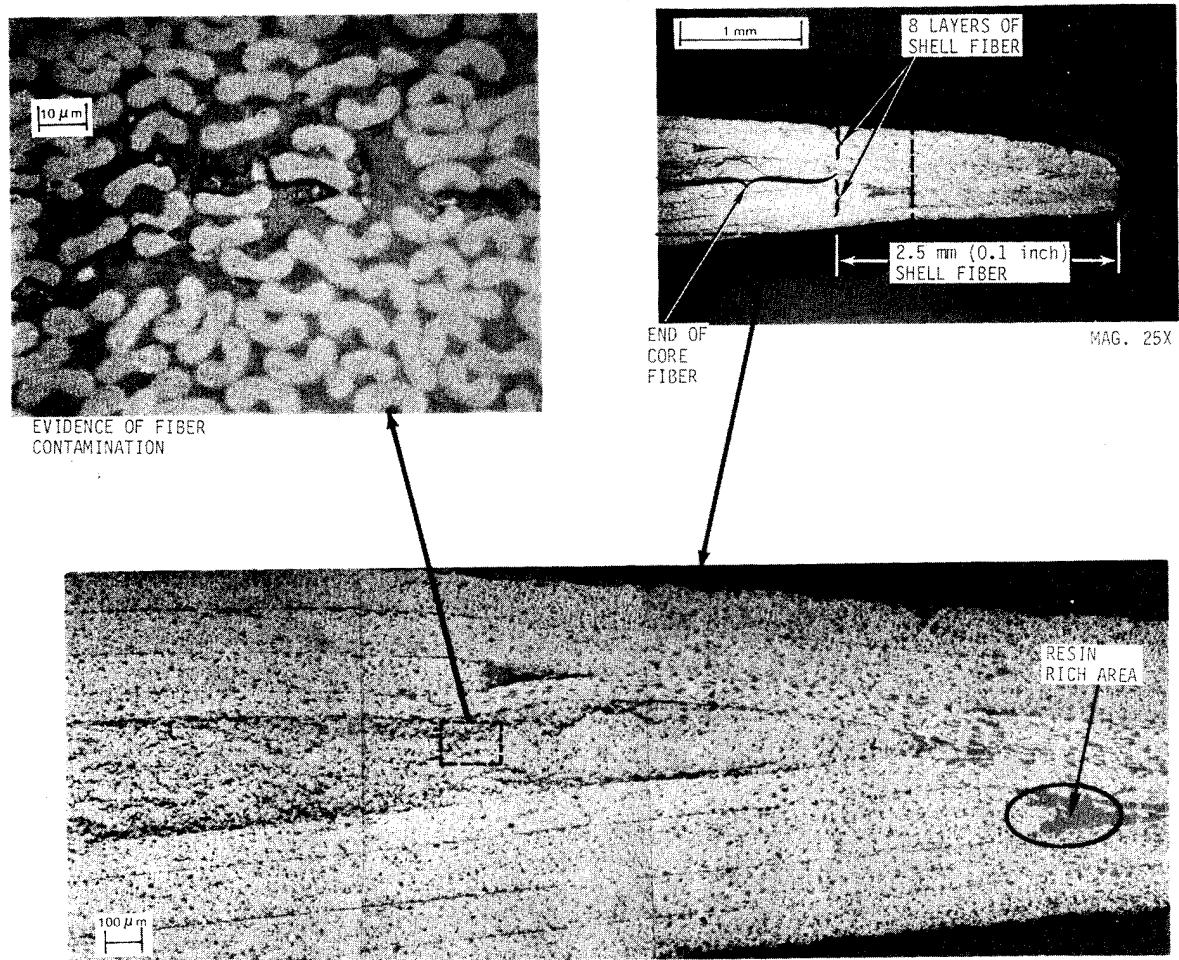


Figure 4-1 Photomicrograph of Typical Cross-Section of Contaminated Fiber 1975 Period Thin Trailing Edge Vane

Mechanical property data were obtained from 15.2 cm x 15.2 cm x 2.03 mm (6 in. x 6 in. x 0.080 in. thick) composite panels fabricated and tested by both vane manufacturers. Sections of these panels were also tested by P&WA. Additional data were obtained directly from sections of vanes. This test approach was taken to ensure that test panel and vane mechanical properties would be representative of the material and process specification established for this part. The critical proper-

ties for a material specification were established as shear, peel and flexure strength as well as modulus of the composite material in dry and wet conditions at room temperature and elevated temperature. Panels fabricated by Great Lakes Carbon and both vane fabricators and tested by vendors and P&WA indicated that the as-fabricated Fortafil 5A graphite composite tested at room temperature exhibited average shear and peel strength of 86.4 MPa (12.5 Ksi) and 1686 N/M (9.6 lbs./in.), respectively. Average flexure strength and modulus of Fortafil 5A graphite were 1162 MPa (169 Ksi) and 160.2 GPa (23.2 msi), respectively (Table 4-I). To further verify the cleanliness of the fiber additional peel testing of 60 v/o Fortafil 5A composite panels with polyurethane bonded to the surface was performed at $+35^{\circ}$ and $+90^{\circ}$ to the fiber direction. Average peel strength, approximately 1925 N/M (11 lbs./in.), was similar for polyurethane removal regardless of fiber orientation (Table 4-II).

Mechanical properties of high modulus Fortafil 5A and intermediate modulus Hercules graphite AS-2, S-glass cloth and S-glass unidirectional fiber were also obtained by P&WA from specimens fabricated by Composites Horizons and TRW. Test data obtained at P&WA for vendor fabricated panels was similar to that obtained at Great Lakes Carbon. The as-fabricated panel properties of AS-2 graphite, S-glass cloth and S-glass unidirectional fiber, all of which were used as shell material, are presented in Table 4-III.

Both TRW and Composites Horizons fabricated specimens for testing at 121°C (250°F). Results indicated that a significant reduction in short beam shear strength for all candidate materials was apparent at 121°C ; Fortafil 5A decreased approximately 30 percent, whereas AS-2, S-glass cloth and S-glass fiber shell decreased 50, 40 and 60 percent, respectively (Tables 4-IV and 4-V). The flexural strength of Fortafil 5A did not change significantly at 121°C ; however, the other three materials experienced a flexure strength decrease of between 30 and 40 percent. Modulus remained relatively constant for three of the four materials; however, S-glass cloth experienced a drop of approximately 40 percent at 121°C .

Mechanical property test specimens of similar thickness to the vane trailing edge were exposed to moisture for three to four weeks at 60°C (140°F)/95 percent relative humidity to simulate the moisture level which would be absorbed by the composite vane after six months of a worst condition ground/flight environment. Moisture absorbed during this period ranged from 0.4 to 0.9 weight percent. Post-test analysis showed a very slight reduction of short beam shear properties of approximately 10 percent; no significant reduction in flexure strength or flexure modulus was apparent for Fortafil 5A, AS-2 graphite or S-glass fiber (Table 4-VI). The flexure strength of S-glass cloth experienced a 20 percent reduction in properties. Trends were similar for both Composites Horizons and TRW fabricated panels.

TABLE 4-I

FORTAFIL 5A COMPOSITE CORE MATERIAL UNIDIRECTIONAL PROPERTIES DATA

Specimens Fabricated by Great Lakes Carbon and Tested at Room Temperature
60 V/O Graphite/Epoxy (EPON 828)

Series Batch	Fiber Density g/cc (lb/ft ³)	TOW Yield m/kg (ft/lb)	Peel Strength* N/M (lbs/in)	Flex Strength MPa (ksi)	Flex Modulus GPa (Msi)	Shear Strength MPa (ksi)
RS 695T	1.8 (112)	228 (340)		1145 (166)	160.0 (23.2)	89.6 (13.0)
				1207 (175)	160.0 (23.2)	92.4 (13.4)
				1172 (170)	164.8 (23.9)	86.9 (12.6)
				1145 (166)	157.2 (22.8)	88.9 (12.9)
				1213 (176)	160.6 (23.3)	91.0 (13.8)
				1131 (164)	156.5 (22.7)	89.6 (13.0)
				1138 (165)	157.2 (22.8)	77.2 (11.2)
				1103 (160)	156.5 (22.7)	79.3 (11.5)
			Avg	1839 (10.5)	1157 (168)	159.1 (23.1)
			Min	1383 (7.9)	1103 (160)	156.5 (22.7)
						86.9 (12.7)
RS 696B	1.8 (112)	217 (324)		1220 (177)	162.0 (23.5)	92.4 (13.4)
				1165 (169)	165.5 (24.0)	85.5 (12.4)
				1000 (145)	156.5 (22.7)	70.3 (10.2)
				1076 (156)	157.9 (22.9)	80.0 (11.6)
				1186 (172)	157.2 (22.8)	86.9 (12.6)
				1158 (168)	157.9 (22.9)	88.9 (12.9)
				1103 (160)	156.5 (22.7)	78.6 (11.4)
				1062 (154)	158.6 (23.0)	80.0 (11.6)
			Avg	1664 (9.5)	1121 (163)	159.0 (23.1)
			Min	946 (5.4)	1000 (145)	156.5 (22.7)
						82.9 (12.0)
RS 697T	1.8 (112)	215 (321)		1241 (180)	160.0 (23.2)	82.7 (12.0)
				1131 (164)	157.2 (22.8)	81.4 (12.0)
				1082 (157)	158.6 (23.0)	91.7 (13.3)
				1207 (175)	157.2 (22.8)	85.5 (12.4)
				1179 (171)	157.2 (22.8)	74.5 (10.8)
				1096 (159)	164.1 (23.8)	75.8 (11.0)
				1207 (175)	160.0 (23.2)	93.8 (12.6)
				1096 (159)	157.9 (22.9)	86.9 (12.6)
			Avg	1594 (9.1)	1155 (168)	159.2 (23.1)
			Min	1051 (6.0)	1082 (157)	157.2 (22.8)
						74.5 (10.8)
RS 697B	1.8 (112)	219 (327)		1255 (182)	164.8 (23.9)	93.8 (13.6)
				1151 (167)	160.0 (23.2)	101.4 (14.7)
				1179 (171)	163.4 (23.7)	80.0 (11.6)
				1172 (170)	165.5 (24.0)	91.0 (13.2)
				1262 (183)	159.2 (23.1)	95.8 (13.9)
				1317 (191)	165.5 (24.0)	91.0 (13.2)
				1144 (166)	164.8 (23.9)	85.5 (12.4)
				1248 (181)	164.1 (23.8)	87.6 (12.7)
			Avg	1646 (9.4)	1216 (176)	163.4 (23.7)
			Min	1243 (7.1)	1144 (166)	159.2 (23.7)
						80.0 (11.6)
OVERALL	Avg. 1.8 (112)	Avg 220 (328)	Avg	1686 (9.6)	1162 (169)	160.2 (23.2)
			Min	946 (5.4)	1000 (145)	156.5 (22.7)

*9.2 mm (0.4 in) and 25.4 mm (1.0 in) wide pulls of 0.25 mm (0.010 in) polyurethane film 90° to fiber direction; single specimen tests

TABLE 4-II

FORTAFIL 5A COMPOSITE DATA

Peel Specimens Fabricated by Composites Horizons and
Tested at Room Temperature; 60 v/o Graphite Epoxy

Shell Material (Urethane Pulled $\pm 35^\circ$ to Fiber Direction)

<u>Sample Number</u>	<u>Average Load at Failure¹</u>	
	<u>N/M (lbs/in)</u>	
1038-16	1926	(11.0)
1038-17	1663	(9.5)
1038-18	1786	(10.2)
1038-19	1996	(11.4)
	Avg.	1842 (10.5)
	Min.	1663 (9.5)

Core Material (Urethane Pulled 90° to Fiber Direction)

<u>Sample Number</u>	<u>Average Load at Failure¹</u>	
	<u>N/M (lbs/in)</u>	
697 TC 200-300	1996	(11.4)
697 BA 0-374	2101	(12.0)
696 BA 300-400	1769	(10.1)
695 TA 100-200	2189	(12.5)
695 TA 500-600	2014	(11.5)
696 BD 200-300	1646	(9.4)
696 TA 200-300	2049	(11.7)
695 TB 0-700	1839	(10.5)
695 TC 500-600	1874	(10.7)
697 TB 300-400	1856	(10.6)
696 BC 100-450	1926	(11.0)
696 BB 100-200	1961	(11.2)
695 TD 300-400	1629	(9.3)
695 TC 200-300	1786	(10.2)
695 TD 600-700	1996	(11.4)
697 TD 0-400	1716	(9.8)
697 BB 0-100	2102	(12.0)
697 BD 100-200	2014	(11.5)
	Avg.	1915 (10.9)
	Min.	1629 (9.3)

¹Strain Rate 5.1 cm/min (2.0 in/min) crosshead speed.

TABLE 4-III

COMPOSITE MECHANICAL PROPERTY DATA

Specimens Fabricated by Composites Horizons and TRW and
Tested by Pratt & Whitney Aircraft at Room Temperature

Specimen No. (1)	Fabri- cation Vendor	Fiber	Flexure Strength MPa (ksi)	Flexure Modulus GPa (msi)	Shear Strength MPa (ksi)
T27, 31	CH	F-5A	1013 (147)	145.5 (21.1)	81.4 (11.8)
T28, 32	CH	F-5A	1096 (159)	149.0 (21.6)	79.3 (11.5)
T43, 47	CH	F-5A	1013 (147)	157.2 (22.8)	80.7 (11.7)
T44, 48	CH	F-5A	- -	144.1 (20.9)	79.3 (11.5)
773-79	TRW	F-5A	- -	- -	80.0 (11.6)
773-79	TRW	F-5A	<u>917 (133)</u>	<u>165.5 (24.0)</u>	<u>80.0 (11.6)</u>
		Avg.	1010 (146)	152.3 (22.1)	80.1 (11.6)
		Min.	917 (133)	144.1 (20.9)	79.3 (11.5)
773-68	TRW	AS-2	2110 (306)	131.0 (19.0)	93.1 (13.5)
773-68	TRW	AS-2	<u>2261 (328)</u>	<u>135.1 (19.6)</u>	<u>87.6 (12.7)</u>
		Avg.	2185 (317)	133.0 (19.3)	90.3 (13.1)
		Min.	2110 (306)	131.0 (19.0)	87.6 (12.7)
T11, 15	CH	S-glass	882 (128)	33.1 (4.8)	65.5 (9.5)
T12, 16	CH	Cloth	<u>910 (132)</u>	<u>32.4 (4.7)</u>	<u>64.1 (9.3)</u>
		Avg.	896 (130)	32.8 (4.8)	64.8 (9.4)
		Min.	882 (128)	32.4 (4.7)	64.1 (9.3)
773-93	TRW	S-glass	1544 (224)	49.0 (7.1)	69.0 (10.0)
773-93	TRW	Unidirec- tional Fiber	<u>1641 (238)</u>	<u>48.3 (7.0)</u>	<u>77.2 (11.2)</u>
		Avg.	1592 (231)	48.7 (7.0)	73.1 (10.6)
		Min.	1641 (238)	48.3 (7.0)	69.0 (10.0)

(1) Each data point is average of two specimens.

TABLE 4-IV

EFFECT OF TEMPERATURE ON MECHANICAL PROPERTIES OF TEST PANELS
FABRICATED WITH FORTAFIL 5A, AS-2 AND S-2 GLASS SHELL MATERIAL

Specimen Fabricated^(a) and Tested by TRW

	F-5A Core TRW ^(b)	AS-2 Shell TRW ^(b)	S-Glass Fiber Shell ^(c) TRW ^(b)
Fiber Lot	RS-695B Ply B, C	76-2	8-5-77B
Resin Lot			
DEN 438A85	TB3/T1306227101	TB3/T1306227101	TB3/T1306227101
DER 331	0610701	0610701	0610701
TONOX 60/40	5017500	5017500	5017500
Panel No.	773-79	773-68	773-64
Resin Solids, w/o	28.0	28.6	27.6
Fiber Vol., %	63.3	62.9	56.2
Flex. Strength ^(a)	MPa (ksi)	MPa (ksi)	MPa (ksi)
RT	1129 (163.8)	1975 (286.4)	1709 (247.9)
250°F	1058 (153.5)	1346 (195.3)	993 (144.0)
Flex. Modulus,	GPa (msi)	GPa (msi)	GPa (msi)
RT	160.0 (23.2)	123.4 (17.9)	53.8 (7.8)
250°F	150.3 (21.8)	131.7 (19.1)	53.1 (7.7)
Short Beam Shear Strength,	MPa (ksi)	MPa (ksi)	MPa (ksi)
RT	74.5 (10.8)	82.0 (11.9)	66.2 (9.6)
250°F	- -	40.7 (5.9)	24.8 (3.6)

NOTES: (a) Normalized to 60 volume percent fiber
(b) All data represent average of three determinations
(c) Owens Corning Glass Roving with 449 size

TABLE 4-V

EFFECT OF TEMPERATURE ON MECHANICAL PROPERTIES OF TEST PANELS
FABRICATED AND TESTED AT COMPOSITES HORIZONS

Panel Material	Test Temp. °C (°F)	Average Flexure Strength MPa (ksi)	Average Flexure Modulus GPa (msi)	Average Shear Strength MPa (ksi)
Graphite Core	RT	1146 (166.2)	137.7 (19.97)	87.6 (12.7)
Fortafil 5A	121 (250)	1168 (169.4)	140.3 (20.35)	58.6 (8.5)
Graphite Shell	RT	1045 (151.6)	149.3 (21.66)	89.1 (12.9)
Fortafil 5A	121 (250)	1112 (161.3)	152.6 (22.14)	60.0 (8.7)
S-Glass Cloth	RT	773 (112.1)	27.30 (3.96)	68.9 (10.0)
Shell	121 (250)	533 (77.3)	16.54 (2.40)	39.3 (5.7)
Style 6581				
Finish G770B				

TABLE 4-VI

P&WA TEST DATA⁽¹⁾ SHOWING EFFECT OF MOISTURE ON ROOM
TEMPERATURE MECHANICAL PROPERTIES OF COMPOSITES HORIZONS AND TRW
FABRICATED PANELS⁽²⁾

Panel Material		Flexural Strength				Flexural Modulus				SBSS			Moisture w/o(3)
		MPa (ksi)				GPa (msi)				MPa (ksi)			
<u>Composites Horizons Panels</u>													
Graphite Core Fortafil 5A	Dry	<u>1013</u> , 1076, 1096, 1124 (<u>147</u>) (156) (159) (163)	<u>140.0</u> , 145.5, 144.8, 153.1 (<u>20.3</u>) (21.1) (21.0) (22.2)				<u>81.4</u> , 83.4, 86.9 (<u>11.8</u>) (12.1) (12.6)						
	Wet	<u>979</u> , 1006, 1076, 1124 (<u>142</u>) (146) (156) (163)	<u>135.8</u> , 137.9, 140.0, 153.1 (<u>19.7</u>) (20.0) (20.3) (22.2)				<u>73.8</u> , 74.5, 79.3 (<u>10.7</u>) (10.8) (11.5)			0.4 - 0.6			
Graphite Shell Fortafil 5A	Dry	<u>930</u> , 945, 1014 (<u>135</u>) (137) (147)	<u>134.4</u> , 144.1, 144.1, 157.2 (<u>19.5</u>) (20.9) (20.9) (22.8)				80.7, 80.7, 79.3, <u>77.9</u> (11.7) (11.7) (11.5) (<u>11.3</u>)						
	Wet	<u>855</u> , 924, 924, 979 (<u>124</u>) (134) (134) (142)	<u>134.4</u> , 142.0, 143.4, 144.8 (<u>19.5</u>) (20.5) (20.8) (21.0)				<u>52.4</u> , 66.9, 73.1, 77.2 (<u>7.6</u>) (9.7) (10.6) (11.2)			0.6 - 0.9			
S-Glass Cloth Shell	Dry	<u>676</u> , 689, 882, 910 (<u>98</u>) (100) (128) (132)	<u>28.9</u> , 29.6, 32.4, 33.1 (<u>4.2</u>) (4.3) (4.7) (4.8)				<u>64.1</u> , 65.5, 65.5, 65.5 (<u>9.3</u>) (9.5) (9.5) (9.5)						
	Wet	<u>593</u> , <u>593</u> , 607, 627 (<u>86</u>) (<u>86</u>) (88) (91)	<u>28.3</u> , <u>28.3</u> , 30.3, 31.7 (<u>4.1</u>) (<u>4.1</u>) (4.4) (4.6)				<u>57.2</u> , 57.9, 58.6, 58.6 (<u>8.3</u>) (8.4) (8.5) (8.5)			0.6 - 0.9			
<u>TRW Panels</u>													
Graphite Core Fortafil 5A	Dry	917 (133)	165 (24)				80.0, 80.0 (11.6) (11.6)						
	Wet	<u>958</u> , 1041 (<u>139</u>) (151)	<u>158.6</u> , 168.2 (<u>23.0</u>) (24.4)				<u>66.9</u> , 68.9 (<u>9.7</u>) (10.0)			0.5			
AS-2 Graphite Shell	Dry	<u>2110</u> , 2261 (<u>306</u>) (328)	<u>131.0</u> , 148.9 (<u>19.0</u>) (21.6)				<u>87.6</u> , 93.1 (<u>12.7</u>) (13.5)						
	Wet	1903 (276)	<u>127.6</u> , 129.6 (<u>18.5</u>) (18.8)				<u>70.3</u> , 71.7 (<u>10.2</u>) (10.4)			0.6			
S-Glass Fiber Shell	Dry	<u>1544</u> , 1641 (<u>224</u>) (238)	48.3, 48.3 (7.0) (7.0)				<u>68.9</u> , 77.2 (<u>10.0</u>) (11.2)						
	Wet	<u>1454</u> , 1503 (<u>211</u>) (218)	<u>53.1</u> , 54.5 (<u>7.7</u>) (7.9)				<u>73.8</u> , 75.2 (<u>10.7</u>) (10.9)			0.4			

(1) Minimum data underlined in each grouping

(2) Panel specimens tested at Pratt & Whitney Aircraft; all panels 2.03 mm (0.080 in.) thick

(3) Specimens gained between 0.4 w/o to 0.9 w/o moisture after exposure at 60°C (140°F)/95% RH for 3-4 weeks

Test sections were removed from the unidirectional core of vanes after fatigue testing was completed to compare vane mechanical properties to test specimen properties. No significant difference was noted between vane and specimen core fiber properties. Specimen properties from vanes which were tested in the wet condition were similar to dry vane properties (Table 4-VII). Density of the vane core section was established at 1.50 \pm 0.05 gm/cc (0.054 \pm 0.002 lb/in³).

4.1.3 Resin Properties

Resin materials were independently selected by Composites Horizons and TRW; both were epoxy novalac systems. Vendors selected their systems to meet the requirements of their processing approach. Composites Horizons pultruded the unidirectional vane core and fabricated ply prepreps for the shell, whereas TRW prepregged individual ply layers for both the core and shell. In addition to ease of processing, cured resin materials were required to have excellent resistance to moisture and experience no glass transition effects within the vane operating temperature range. Good strength and ductility were also required.

TABLE 4-VII

MECHANICAL PROPERTIES OF UNIDIRECTIONAL FORTAFIL 5A CORE COMPOSITE
SECTIONS FROM VANES AFTER FATIGUE TEST

Vane Serial Number	Vane Test Condition	Density		Flexure Strength ⁽¹⁾		Flexure Modulus		Shear Strength	
		gm/cc		MPa (ksi)		GPa (msi)		MPa (ksi)	
<u>Composites Horizons</u>									
30	Dry	1.48	1.50	1055	(153)	147.6	(21.4)	80.0	(11.6)
		1.52	1.52	1144	(166)	155.8	(22.6)	88.9	(12.9)
11	Dry			1034	(150)	146.2	(21.2)	88.2	(12.8)
				1048	(152)	156.5	(22.7)	88.2	(12.8)
32	Wet	1.51	1.51	827	(120)	143.4	(20.8)	80.7	(11.7)
		1.51	1.54	910	(132)	150.3	(21.8)	85.5	(12.4)
<u>TRW</u>									
2-003	Dry	1.50	1.50	896	(130)	153.8	(22.3)	83.4	(12.1)
		1.51	1.52	1076	(156)	154.4	(22.4)	83.4	(12.1)
2-007	Dry	1.43	1.46	827	(120)	138.6	(20.1)	66.2	(9.6)
		1.46	1.48	1041	(151)	154.4	(22.4)	68.3	(9.9)
2-008	Wet			1076	(156)	154.4	(22.4)	84.8	(12.3)
				1158	(168)	155.1	(22.5)	88.9	(12.9)

(1) Minimum data underlined for each test vendor

Samples of neat resin material, cut from 0.1 inch thick slabs fabricated by both vendors, were exposed to 60°C (140°F), 95 percent relative humidity conditions for various periods of time. Glass transition temperature (T_g), using the Perkin Elmer TMS-1 Thermal Mechanical Analyzer in the penetration mode, was determined for increasing levels of moisture in both epoxy systems (Table 4-VIII). The T_g of both resin systems responded similarly to moisture gain (Figure 4-2). However, these reductions in T_g were not expected to affect material performance since the lowest wet glass transition temperature was higher than the maximum expected operating vane temperature of 88°C (190°F).

TABLE 4-VIII

EFFECT OF MOISTURE ON GLASS TRANSITION TEMPERATURE

CH 4010 ResinTRW Resin

Composition DEN 438, 50 Parts; DER 331, 50 Parts;
 Proprietary to Composites Horizons TONOX 60/40, 20 Parts

Moisture, w/o	T _g °C (°F)	Moisture, w/o	T _g °C (°F)
Dry	207 (405)	Dry	178 (350)
0.8	199 (390)	0.9	171 (340)
1.0	191 (375)	1.0	168 (335)
1.0	188 (370)	1.1	165 (330)
1.3	185 (365)	1.2	160 (320)
1.4	185 (365)	1.3	160 (320)
1.6	185 (365)	1.4	160 (320)
1.6	185 (365)	1.5	160 (320)

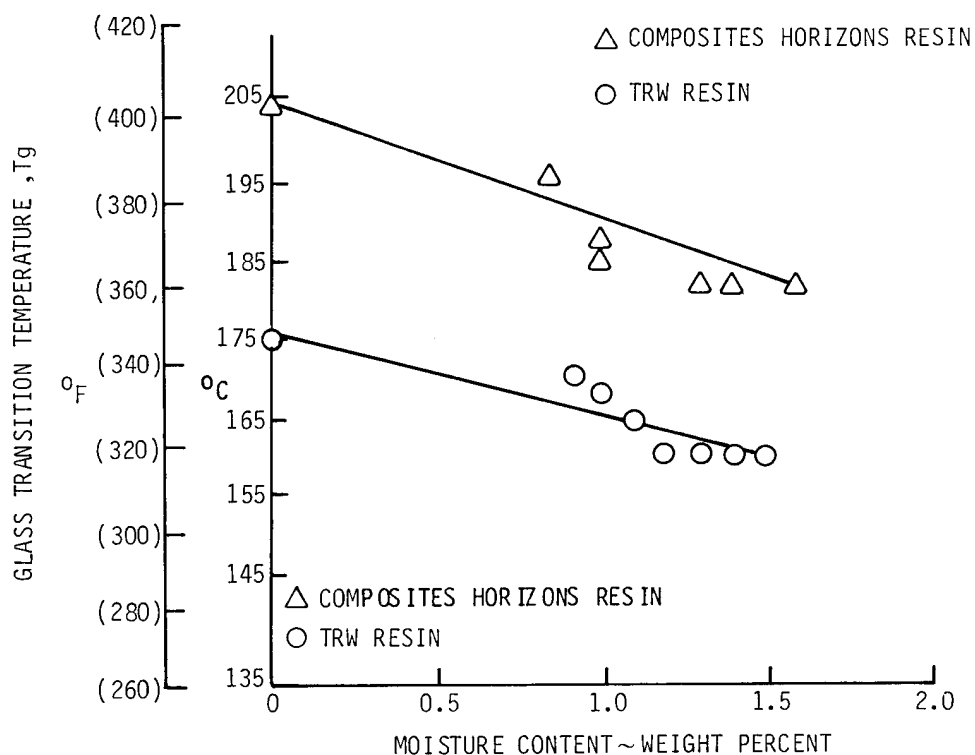


Figure 4-2

Effect of Moisture on Glass Transition Temperature
 of Epoxy Novalac Resin Systems

A comparison was made of glass transition temperatures for neat resin samples exuded from the vane molds during fabrication, composite panels and composite vane sections in dry and wet conditions (Table 4-IX). The exuded resin from ten Composites Horizons vanes showed good glass transition temperature reproducibility and excellent agreement with neat resin test specimen data reported above. Introduction of 1.3 to 1.6 weight percent moisture in the neat exuded resin resulted in a drop of T_g to 185°C (365°F). Additional tests were performed by evaluating a moisture level of 0.6 to 0.8 w/o in composite panels as representative equilibrium moisture expected in a typical JT9D composite vane after six months of service operation. Data indicated a small decrease in glass transition temperature from 207°C (405°F) to 188°C (370°F) for these conditions. Evaluation of sections cut from composite vanes indicated that glass transition measurements can be made on either the composite material or exuded resin and provide identical results. Evaluation of penetration mode expansion curves used to obtain glass transition temperature revealed an increase in expansion characteristics of the wet composite near the boiling point of water (Figure 4-3). However, neither the minimum wet glass transition temperature of 185°C (365°F) nor the expansion increase due to moisture at 100°C (212°F) are expected to affect vane mechanical properties at maximum operating temperature of 88°C (190°F).

TABLE 4-IX
EFFECT OF MOISTURE ON GLASS TRANSITION TEMPERATURE OF
CH 4010 NEAT RESIN AND COMPOSITES HORIZONS VANES/PANELS

	Vane or Panel Serial Number	Exuded Resin		Composite Panel		Composite Vanes
		Dry °C (°F)	Wet (1) °C (°F)	Dry °C (°F)	Wet (2) °C (°F)	Dry °C (°F)
<u>All Graphite Component:</u>						
Vanes	30	207 (405)				202 (395), 210 (410)
	32	210 (410)				207 (405)
	34	207 (405)				204 (400), 204 (400)
	35	204 (400)				207 (405)
	36	210 (410)				207 (405)
Pre-Core Resin	9, 16			202 (395) 202 (395)	199 (390)	
Panel-Shell Resin	7, 11			202 (395) 207 (405)	188 (370) 207 (405)	
<u>Glass-Graphite Composite:</u>						
Vanes	7	204 (400)				207 (405)
	8	199 (390)				207 (405)
	9	207 (405)	185 (365)			204 (400)
	11	204 (400)				-
	12	204 (400)				207 (405)
Panel-Shell Resin	3, 12			202 (395) 204 (400)	196 (385) 207 (405)	

(1) 1.3 - 1.6 w/o moisture

(2) 0.6 - 0.8 w/o moisture

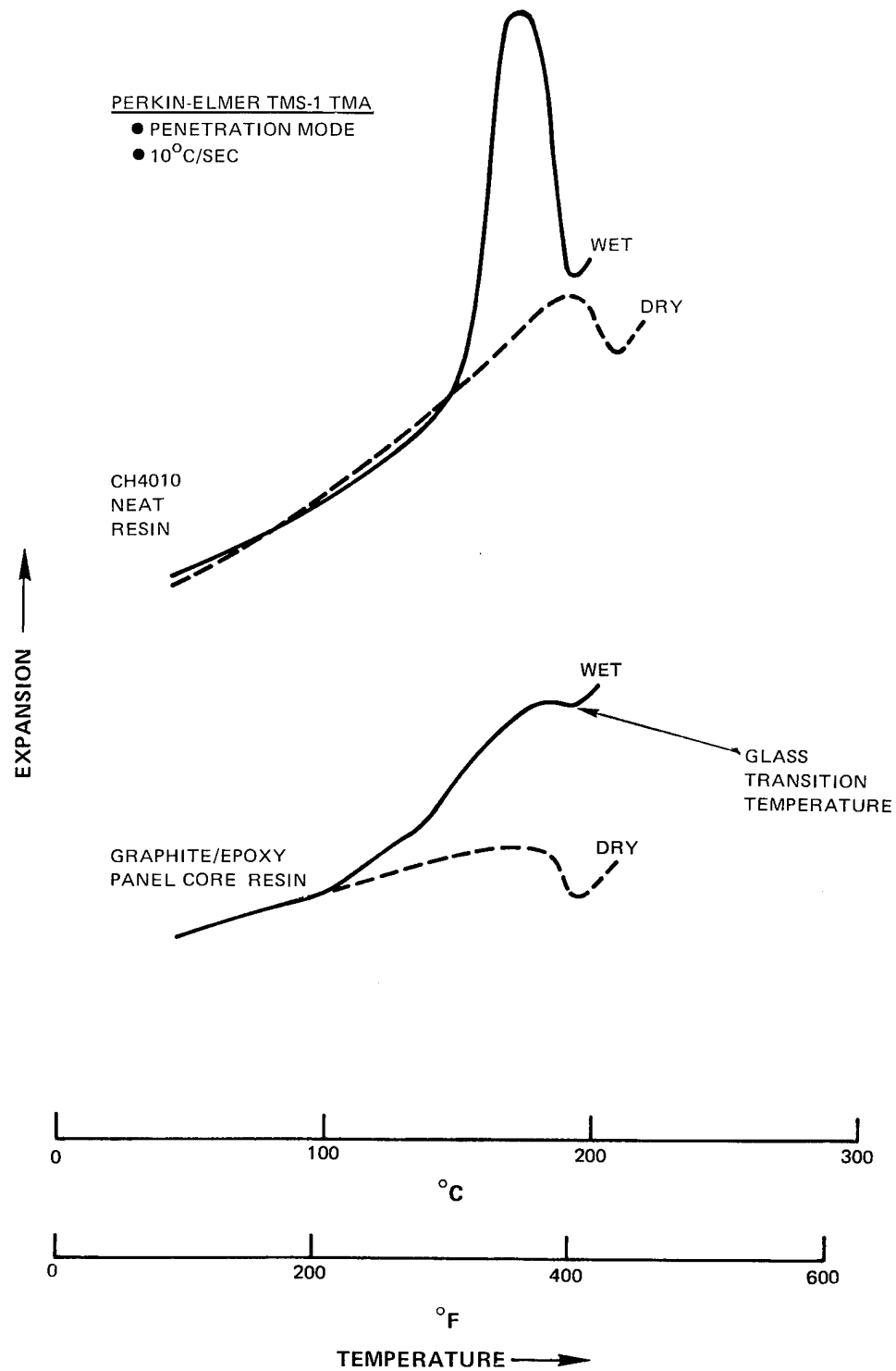


Figure 4-3 Thermomechanical Trace of Composite Horizons Neat Resin and Composite Panels

Characteristic infrared spectra were obtained for each of the resin formulations for potential use in raw material process control testing. The spectra signatures confirm the similarities of the candidate epoxy novalac systems (Figure 4-4). Only one different peak grouping, in the 1105 to 1145 cm^{-1} frequency range, was noted for CH resin and not for the TRW selected resin. This peak grouping can be related to the presence of an aromatic sulfone (S-O stretch). Aromatic sulfones in epoxy novalac systems contribute to higher glass transition temperatures.

Neat resin mechanical properties were obtained from cast slabs fabricated by both vendors and tested by P&WA. The data confirmed the similar characteristics of both resin systems (Table 4-X).

The mechanical and physical property data obtained during material acceptance and characterization testing and earlier data were used to establish a model specification (PWA 125) for graphite fiber epoxy composite materials. The model specification is presented in Appendix A.

TABLE 4-X

NEAT EPOXY RESIN MECHANICAL PROPERTIES*

	Ultimate Tensile		Modulus		Elongation, %	
	MPa (ksi)		GPa (msi)			
	Tested by		Tested by		Tested by	
	P&WA	TRW	P&WA	TRW	P&WA	TRW
<u>Specimen</u>						
<u>Fabricator</u>						
Composites	86.2 (12.5)		3.86 (0.56)		3.6	
Horizons	68.9 (10.0)		3.86 (0.56)		2.5	
	73.8 (10.7)		3.58 (0.52)		2.6	
TRW	89.6 (13.0)	89.6 (13.0)	3.58 (0.52)	3.52 (0.51)	3.9	4.8
	65.5 (9.5)	84.1 (12.2)	3.58 (0.52)	3.24 (0.47)	2.7	3.7
	51.0 (7.4)	68.9 (10.0)	3.45 (0.50)	3.58 (0.52)	1.7	2.6
	54.5 (7.9)		3.58 (0.52)		2.0	

*Specimen size 3.18 cm (1.25 in.) gage length; 0.95 cm (0.375 in.) wide; 2.8 mm (0.110 in.) thick

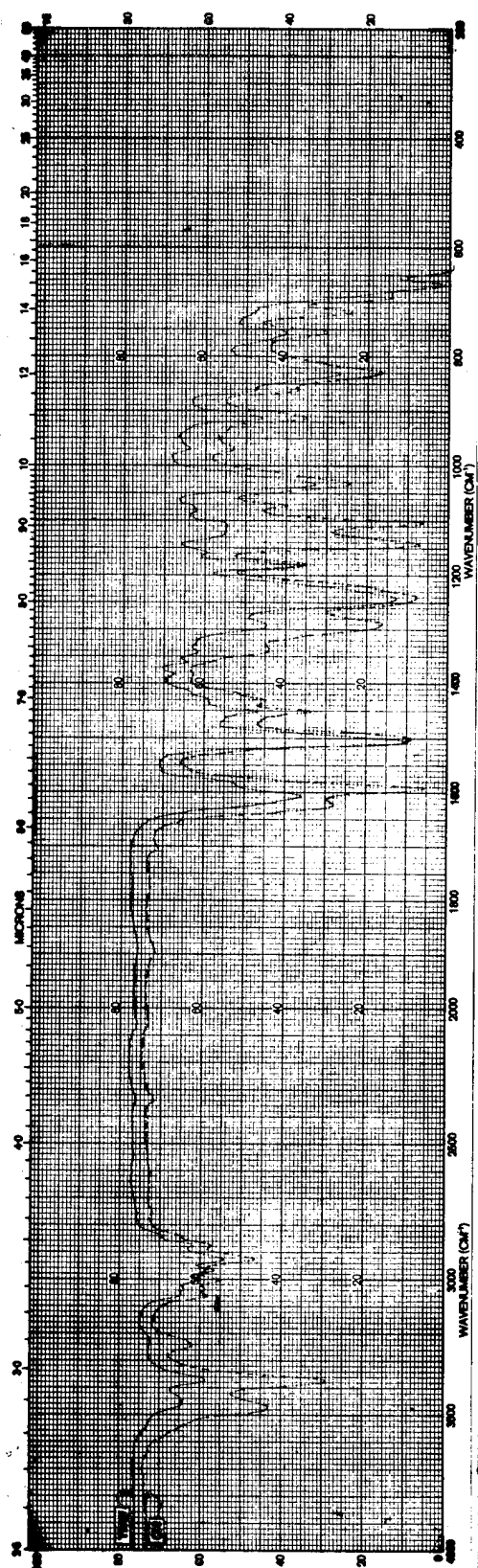


Figure 4-4 Infrared Analysis of TRW and Composites Horizons Resin Systems

4.2 VANE FABRICATION

4.2.1 Introduction

Two vane fabricators were selected based on their previous manufacturing experience with composite fan exit guide vanes. Each fabricator, Composites Horizons and TRW, delivered a total of 13 vanes to Pratt & Whitney Aircraft for evaluation. The first vane delivered by each vendor confirmed the dimensional requirements for part fabrication and demonstrated composite microstructure quality. Slight dimensional deviations noted for the TRW fabricated vanes were not sufficient to affect the results of the materials, processing or structural evaluation programs. After approval of the fabrication procedure, two vanes representing the candidate material and ply lay-up from each vendor were fabricated with intentional flaws of various types and sizes at different locations. These flawed vanes were subjected to a variety of nondestructive inspection techniques by both vendors and P&WA to determine inspection sensitivity levels. The remaining ten vanes from each vendor were fabricated in two groups of five for each material ply lay-up selected. Parts were inspected and sent to Pratt & Whitney Aircraft for pre-test analysis, fatigue test and post-test inspection. Each fabricator, at the conclusion of the program, submitted a projected price estimate for lots of 1000 vanes/month.

Both Composites Horizons and TRW used compression molding tooling and processing to fabricate parts for the subject program. Unidirectional fiber and cloth test panels were fabricated and evaluated for each batch of fiber and for each batch of resin used for vane fabrication. Results of these panel properties were presented in Section 4.1.

The 13 vanes prepared by each vendor were fabricated in the following sequence. The first vane made confirmed the airfoil dimensional and composite microstructure requirements; second and third vanes were made representing the two material and ply lay-up configurations with intentional flaws for nondestructive testing; vanes 4 through 13 were fabricated to represent the two candidate configurations of five vanes each from each vendor.

4.2.2 Vane Material Selection

Each vendor used a common vane core material, Fortafil 5A. Four different shell materials were selected; two by each vendor. Ply lay-up procedures, fiber orientation and resin systems were varied between vendors. Details of these vane fabrication variables are shown in Tables 4-XI.

Broadgoods at TRW to be used for core and shell construction were fabricated on a 152 cm (5 ft) long by 152 cm (5 ft) diameter drum and prepregged with a measured resin mixture of DEN 438, DER 331 and TONOX 60/40. Similarly, broadgoods at Composites Horizons for shell construction only were fabricated on a 91.4 cm (3 ft) diameter drum and prepregged with CH 4010 epoxy novalac formulated by Composites Horizons.

TABLE 4-XI

VANE FABRICATION VARIABLES

<u>Vendor</u>	<u>Core Material</u>	<u>Shell Material</u>	<u>Fiber Orientation</u>	<u>Resin</u>	<u>Cure Conditions</u>
Composites Horizons	Pultruded Fortafil 5A	Fortafil 5A Prepreg Plies	+35,-35,-35,+35 (4 plies)	CH 4010	Proprietary
	Pultruded Fortafil 5A	S-glass cloth Style 6581	+45 (2 plies)		
TRW	Ply prepreg Fortafil 5A	AS-2 Graphite Prepreg plies	+30,-30,+30,-30 (4 plies)	DEN 438 +	2 Hrs at 149°C (300°F) +
	Ply prepreg Fortafil 5A	Owens Corning S2 Glass Roving with 449 Size	+45 (2 plies)	DER 331 + TONOX 60/40	16 Hrs at 154°C (310°F)

4.2.3 Vane Fabrication Sequence

After materials acceptance, graphite fibers for the core section of vanes to be fabricated by Composites Horizons were prepregged by pultrusion through a liquid resin bath (Figure 4-5). The pultruded unidirectional core was then preformed to airfoil shape cut to length and laid up with either four 0.13 mm (0.005 inch) thick cross ply shells of prepregged graphite or two 0.25 mm (0.010 inch thick) cross ply shells of prepregged glass. A 0.25 mm (0.010 in.) thick AMS 4015 aluminum leading edge (Figure 4-6) was included in the one step compression molding operation in a resistance heated tool (Figure 4-7). The TRW composite part was fabricated by laying up the unidirectional core fiber and the cross-ply shell fibers, as shown in Figure 4-8, and folding the "B" staged ply assembly along the trailing edge section to form the airfoil. An aluminum leading edge was then placed over the leading edge section of the uncured vane. The assembly was placed in a resistance heated mold for bonding (Figure 4-9). A summary of the vane fabrication sequence for Composite Horizons and TRW parts is shown in Figure 4-10 and 4-11. Details of fabrication steps are presented in Appendix B.

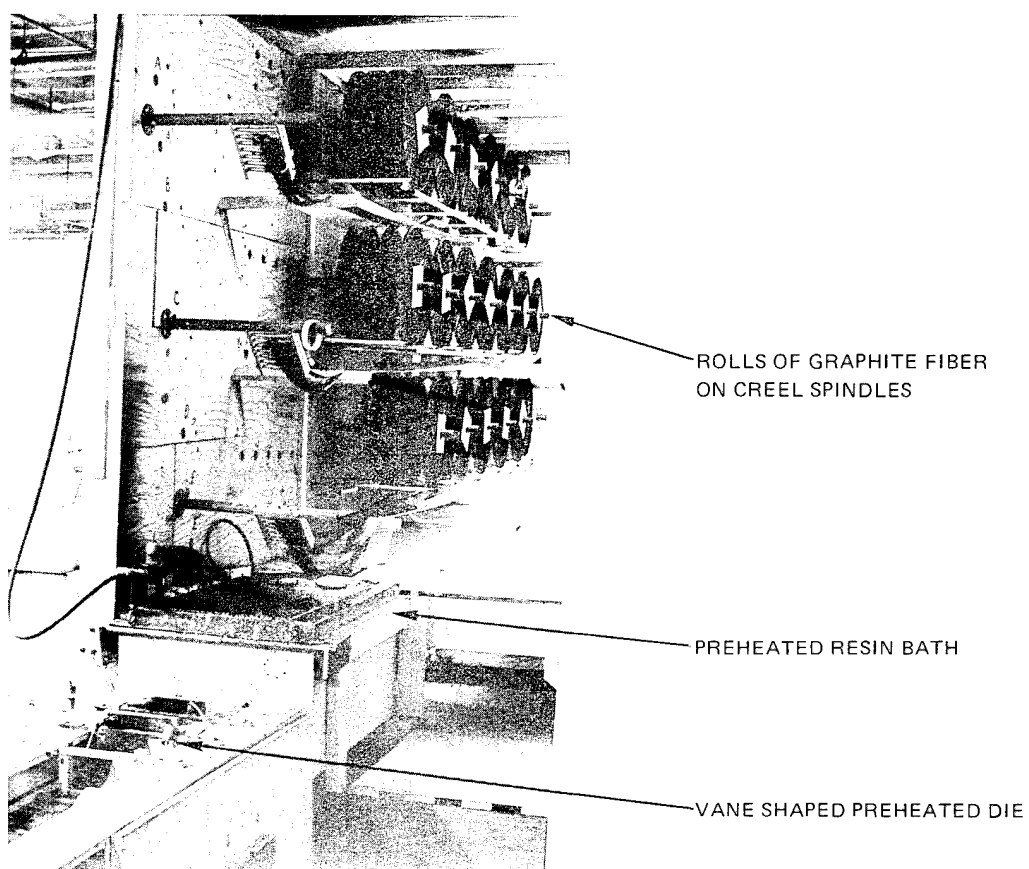


Figure 4-5 Composites Horizons Pultrusion Equipment

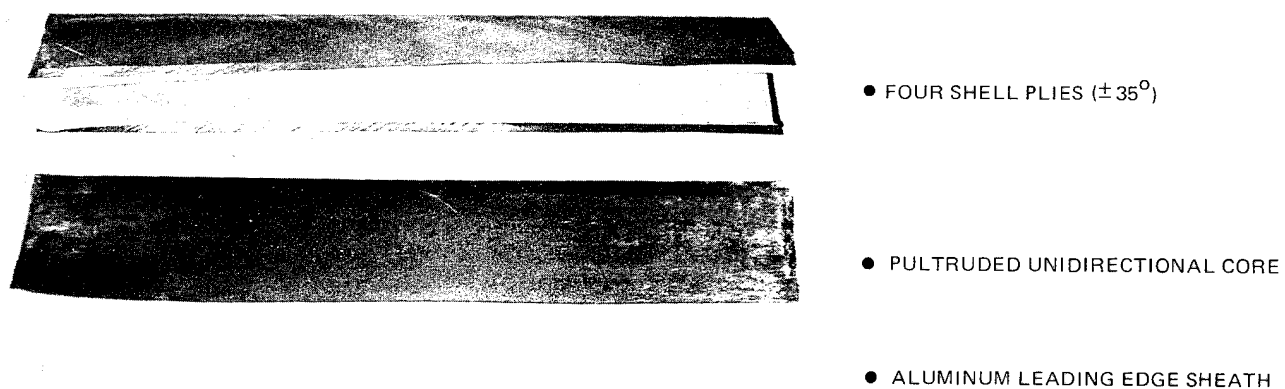


Figure 4-6 Composites Horizons Graphite/Epoxy Vane Composites

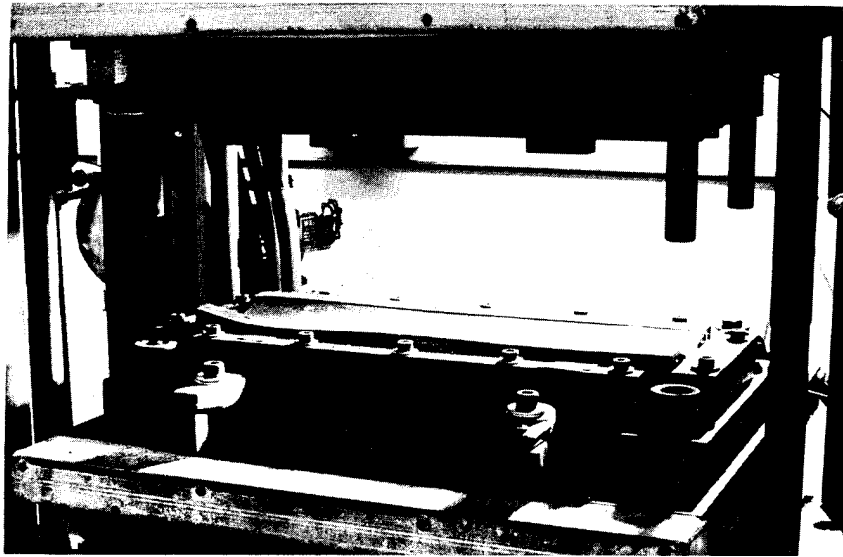


Figure 4-7 Composites Horizons Vane Molding Tool and Press

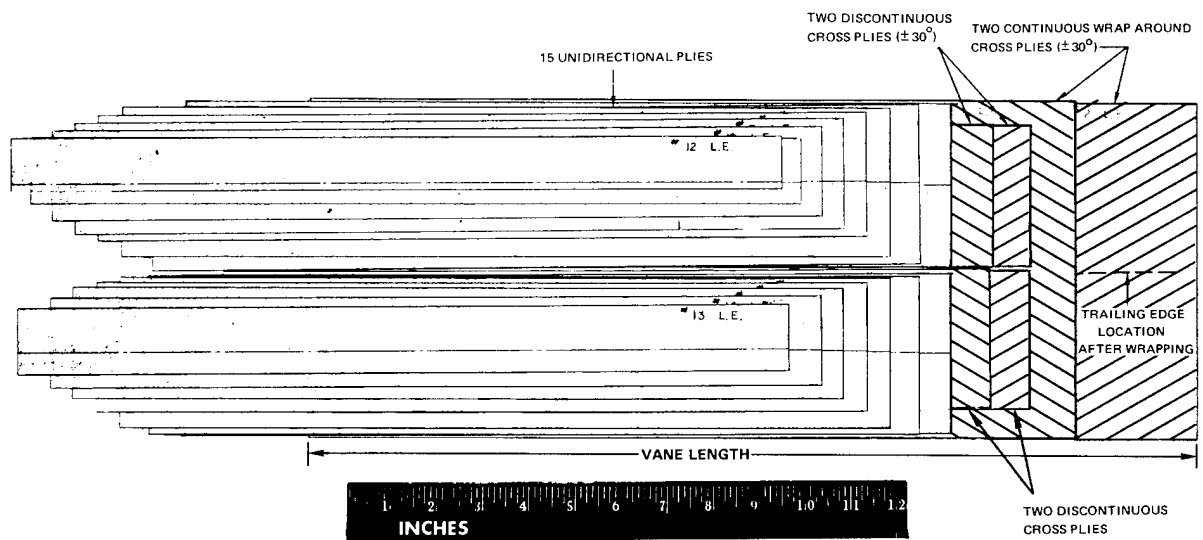


Figure 4-8 Elongated View of TRW Vane Ply Layup Sequence

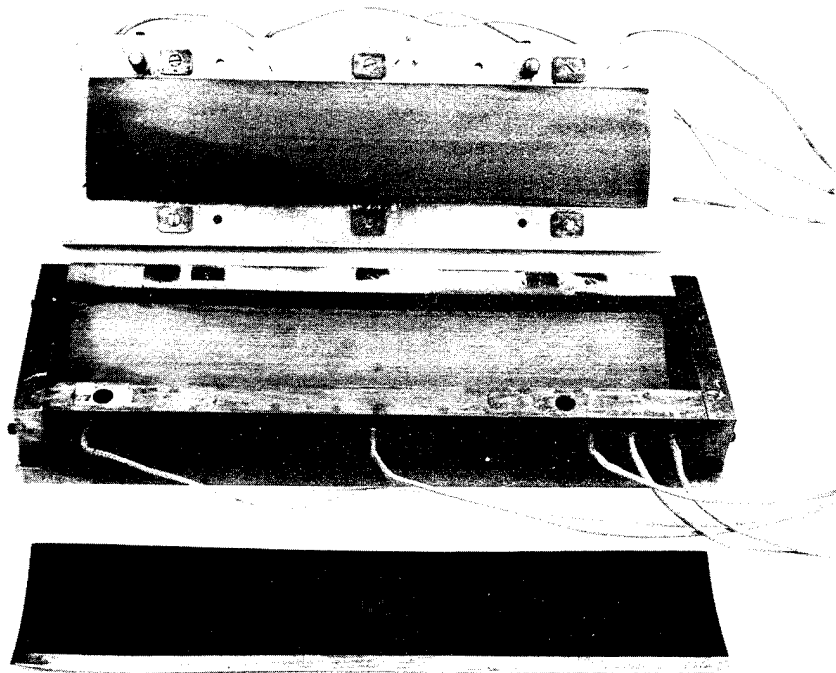


Figure 4-9 TRW Mold and Composite Fan Exit Guide Vane

Vanes were identified by vendors using the following serial number system.

<u>Vendor</u>	<u>Material</u>	<u>Part Function</u>	<u>S/N</u>
Composites Horizons	All Graphite	Tool Trial	28
		NDI	4
		Fatigue Test	30
			32
			34
			35
			36
	Fiberglass/ Graphite	NDI	1
		Fatigue Test	7
			8
			9
			11
			12
TRW	All Graphite	Tool Trial	1-00A
		NDI	1-001
		Fatigue Test	1-003
			1-004
			1-006
			1-008
			1-0011
	Fiberglass/ Graphite	NDI	2-001
		Fatigue Test	2-002
			2-003
			2-007
			2-005
			2-008

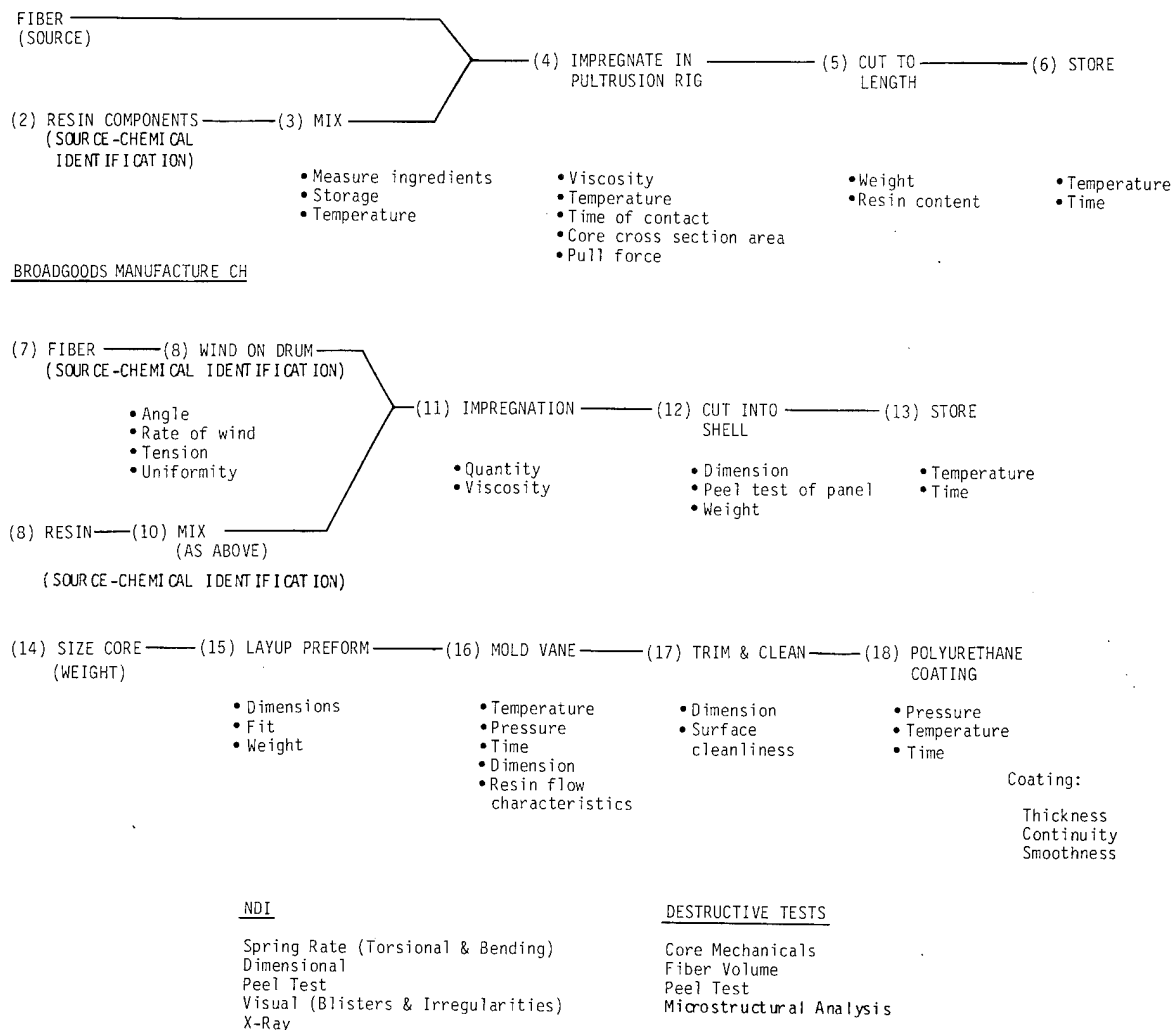


Figure 4-10 Composites Horizons Fan Exit Guide Vane Fabrication Sequence

4.2.4 Economic Analysis

Both vendors were asked to submit production fabrication price estimates for all four material/design configuration vanes at the conclusion of their technical effort. Projections were requested on the basis of delivery of 1000 vanes/month starting in 1979. Composite part price information was compared to current aluminum fan exit guide vane pricing. A summary of comparative pricing is tabulated below. Composite parts are priced from 1.7 to 3.3 times aluminum depending on vendor, vane material and production date. The increased price for composites compared to aluminum is considered a favorable price to weight trade for advanced materials in gas turbine engines.

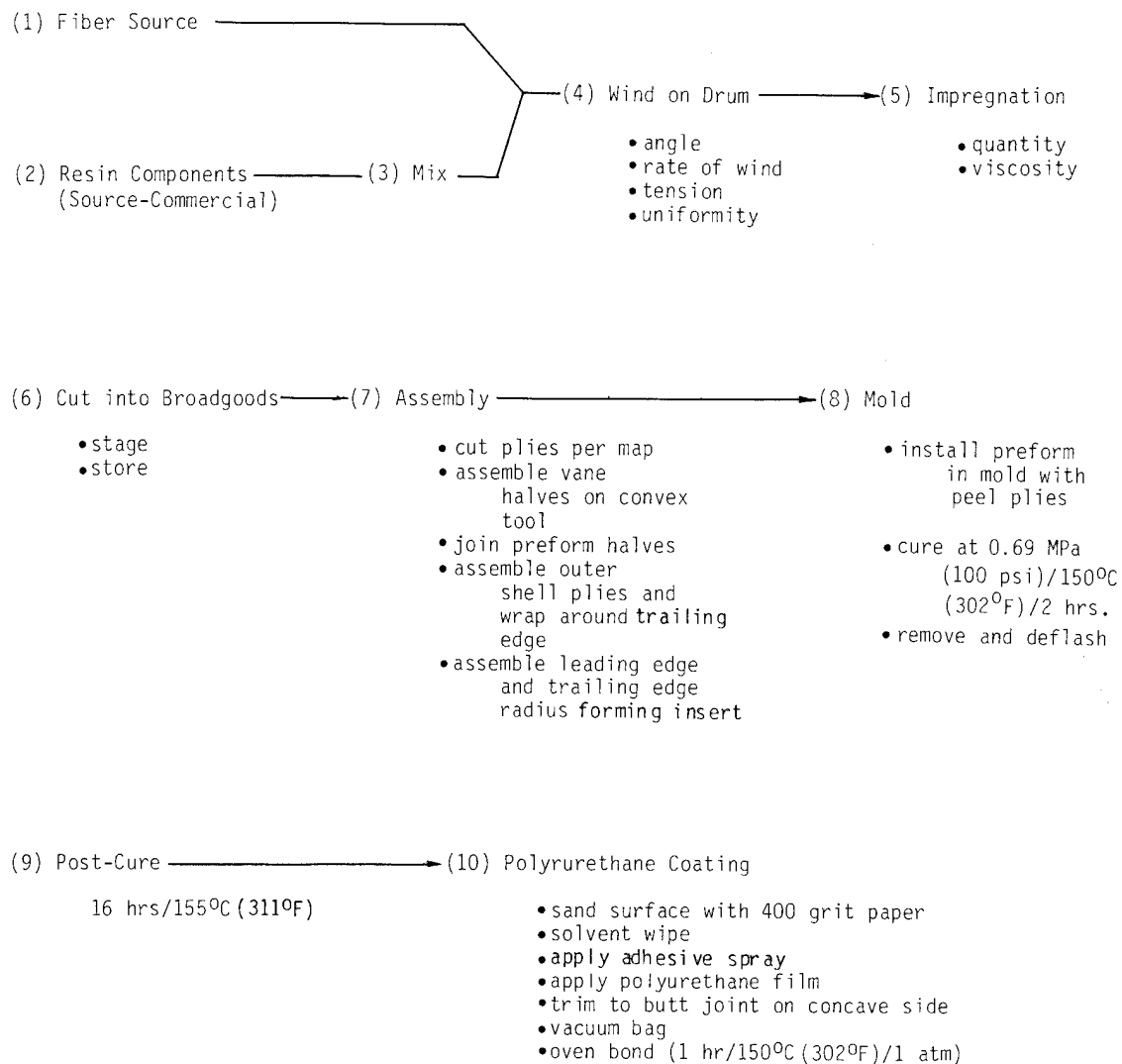


Figure 4-11 TRW Fan Exit Guide Vane Fabrication Sequence

RATIO OF COMPOSITE ALUMINUM VANE PRICE

	Vendor A		Vendor B ⁽²⁾
	<u>1979 Delivery</u>	<u>1980 Delivery⁽¹⁾</u>	<u>1980 Delivery</u>
Aluminum	1	1	1
All Graphite	3.3	2.6	2.0
Glass/Graphite	3.0	2.3	1.7

¹Additional equipment to improve production efficiency

²Vendor B would not be ready to deliver production parts in 1979 at competitive prices without plant equipment change; 1980 prices reflect incorporation of those changes.

4.3 INSPECTION OF FABRICATED VANES

4.3.1 Dimensional Requirements and Weight Control

Both vendors manufactured composite vanes using nonmetallic "soft" tooling. Composites Horizons fabricated their tool from blueprints (P/N 762788) supplied by Pratt & Whitney Aircraft. TRW fabricated a tool by referencing dimensions on a composite part furnished by Pratt & Whitney Aircraft. Dimensional readings at a minimum of three vane sections (Table 4-XII) were obtained on typical CH and TRW vanes for chord length "M" (Figure 4-12). Although some tolerance variation did exist, the effect of these deviations on structural integrity were considered insignificant. The largest tolerance variation was less than 2.54 mm (0.1 in.) reduced chord dimension at midchord on the TRW vane. This reduced section dimension was due to the compounding of tolerance losses when TRW made their mold from part dimensions rather than from blueprints. The narrower midchord section of the TRW vane resulted in a slight inward bow at the trailing edge midspan. This caused some fiber lay-up problems which in turn were seen radiographically as wrinkling of shell wrapped fiber near the trailing edge. However, regardless of the dimensional and process problems there was no apparent effect on the fatigue strain capability of the part as described in section 5.1.4. No significant variations were detected in leading or trailing edge radius when compared to blueprint requirements.

Chordal vane thickness and shell thickness, at four positions (A-D) from trailing edge to leading edge (Figure 4-12), were obtained by microexamination for each uniform cross section vane design. A tabulation of these data are presented in Table 4-XIII.

TABLE 4-XII
COMPARISON OF CHORD LENGTH "M" OF MANUFACTURED VANES
TO BLUEPRINT REQUIREMENTS

<u>Span Section</u>	<u>Blueprint Requirement, cm (inches)</u>	<u>Typical Vane Actual cm (inches)</u>	
		<u>TRW</u>	<u>CH</u>
Inboard	9.157 \pm 0.076 (3.605 \pm 0.030)	9.062 (3.568)	9.073 (3.572)
Mid-Airfoil	9.157 \pm 0.076 (3.605 \pm 0.030)	8.910 (3.508)	9.182 (3.615)
Outboard	9.166 \pm 0.076, 0.127 (3.609 \pm 0.030, 0.050)	9.037 (3.558)	9.182 (3.615)

DIMENSIONS: mm (in.)

TER = Trailing Edge Radius

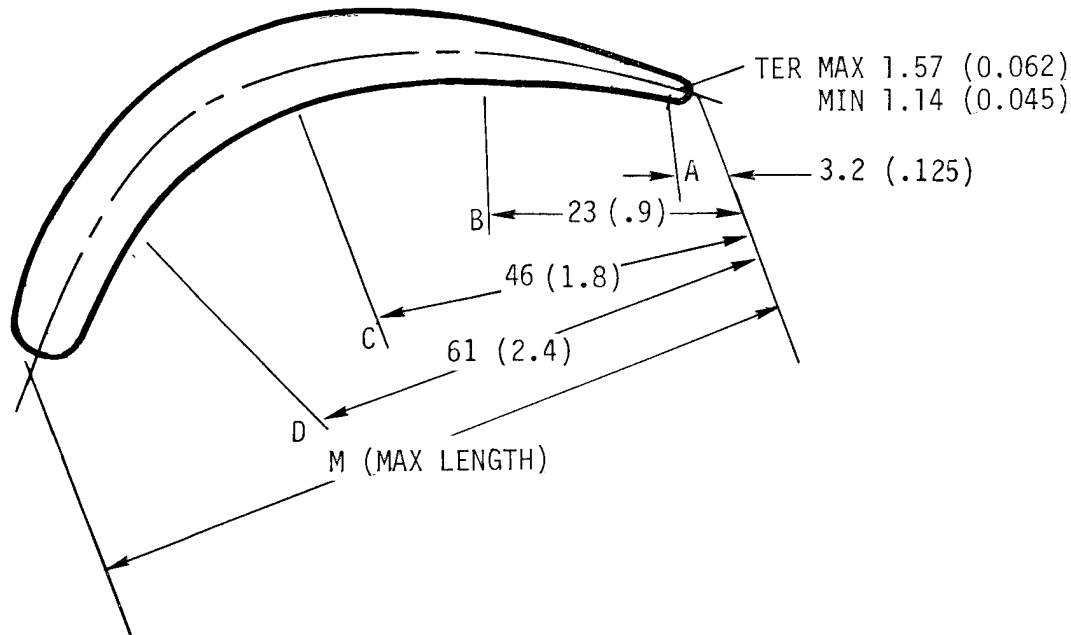


Figure 4-12 Typical Airfoil Section

TABLE 4 X-III

COMPARISON OF SHELL FIBER THICKNESS TO TOTAL
VANE THICKNESS AT FOUR CHORDAL VANE SECTIONS

Vane Configuration Core/Shell Modulus	Shell Orientation/ Number of Plies	Chordal Vane Section Thickness mm (mils)			
		A	B	C	D
138 GPa/138 GPa					
Total		2.08(82)	3.45(136)	4.76(187)	4.67(185)
Shell	+35,-35,-35,+35/4 plies	0.49(19)	0.46(18)	0.49(19)	0.46(18)
138 GPa/124 GPa					
Total		2.16(85)	3.48(137)	4.9(193)	4.89(193)
Shell	+30,-30,+30,-30/4 plies	0.36(14)	0.43(17)	0.46(18)	0.48(19)
138 GPa/48 GPa					
Total		2.44(96)	3.70(146)	5.03(198)	5.0(197)
Shell	+45,-45/2 plies	0.58(23)	0.56(22)	0.58(23)	0.59(23)
138 GPa/28GPa					
Total		2.13(84)	3.63(143)	4.93(194)	4.81(190)
Shell	+45,-45/2 plies	0.33(13)	0.41(16)	0.43(17)	0.43(17)

In addition to dimensional analysis each vane was weighed as a further indicator of quality control (Table 4-XIV). Composites Horizons vanes exhibited less weight scatter than TRW vanes. The range of weight variation of Composites Horizons graphite and fiberglass-graphite/epoxy vanes was 3.6 percent and 2.5 percent, respectively. Comparison of the average weight of a graphite/epoxy vane 280 gms (0.617 lbs) to an aluminum vane 533 gms (1.174 lbs) of similar geometry indicated a difference of 253 gms (0.557 lbs). For an engine with 96 vanes weight saving of composite materials over aluminum was 24.2 kg (53 lbs).

4.3.2 Nondestructive Evaluation

The objective of the nondestructive inspection (NDI) and evaluation portion of the program was to determine detection sensitivity for various size and shape flaws located in different sections of the airfoil by using currently available inspection techniques. This baseline of flaw detection sensitivity was established by intentionally introducing flaws into four airfoils which represented different materials, ply lay-ups, and vendor fabrication techniques. The balance of sound vanes fabricated in the program were then inspected prior to and after fatigue testing and nondestructive test results were compared to data obtained from the NDI standard vanes.

TABLE 4-XIV

VANE WEIGHT, gms

	<u>Composite Horizons</u> <u>Vanes</u>		<u>TRW Vanes</u>	
	<u>Serial</u> <u>Number</u>	<u>Weight</u> <u>gms</u>	<u>Serial</u> <u>Number</u>	<u>Weight</u> <u>gms</u>
All Graphite				
	30	278	1-003	286
	32	282	1-004	285
	34	279	1-006	294
	35	284	1-008	298
	36	274	1-011	307
	Avg.	280		294
Glass Shell/Graphite Core				
	7	280	2-002	306
	8	288	2-003	303
	9	284	2-005	322
	11	283	2-007	331
	12	290	2-008	316
	Avg	285		316

Each vane manufacturer was presented with a similar plan as to the general location, type and size of defect which should be intentionally introduced in each of their two candidate vane configurations. The methods by which flaws were introduced varied and reflected each vendors' prior composite experience. Flaws were categorized in the following way:

1. porosity/inclusions
2. core to shell disbonds, delamination
3. misaligned plys
4. resin-rich areas
5. core matrix cracking

For the most part, flaw patterns introduced by Composites Horizons and TRW were repeated on both sides of each vane midspan so as to evaluate inspection sensitivity under uncoated and polyurethane coated conditions. Schematic diagrams showing flaw types and location are illustrated in Figures 4-13 and 4-14. Some foreign nonmetallic materials, teflon, glass microspheres and syntactic foam were introduced to simulate intentionally flawed regions. However, whenever possible, efforts were made to introduce flaws without foreign material.

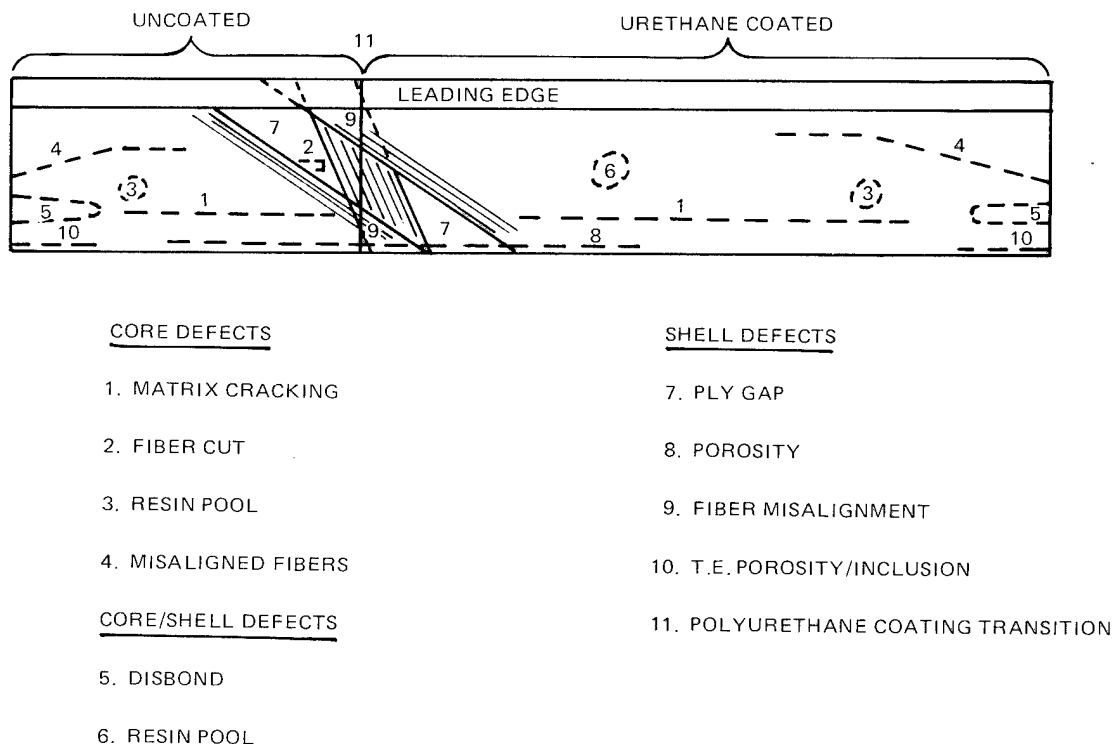


Figure 4-13 Composites Horizons Defect Vane Flaw Location and Identification Map

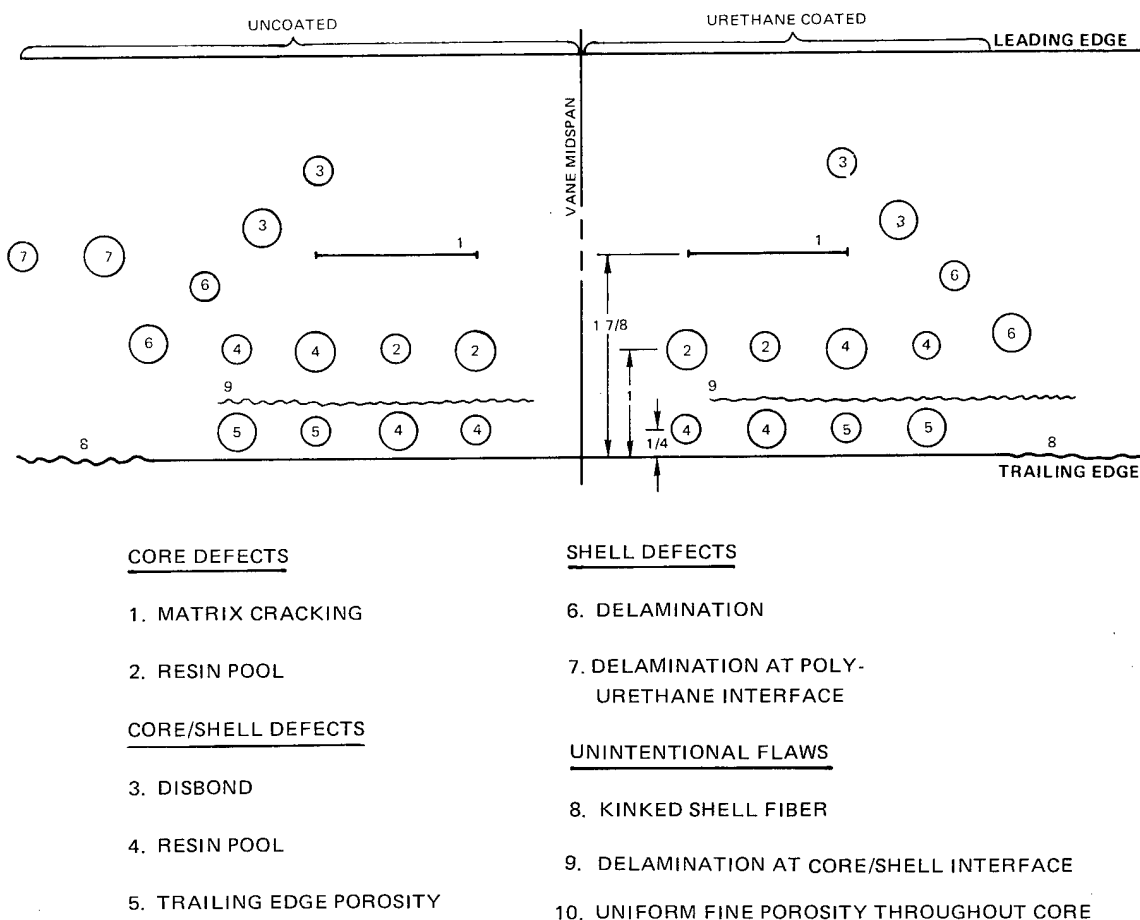


Figure 4-14 TRW Defect Vane Flaw Location and Identification Map

Defects were further grouped for cataloging based on their location at either the core, core/shell interface or shell. NDI standard vanes fabricated by Composites Horizons contained defects introduced without, for the most part, foreign material. TRW's NDI standard vanes incorporated more foreign material to establish flawed areas. In addition, several variations in quality which were not planned for these vanes were detectable. These deviations are tabulated in a subsequent portion of the text.

Vane physical properties and part shape were considered in selecting NDI techniques that would provide maximum inspection sensitivity. The differences between fiberglass and graphite shell material and the presence of polyurethane coating were also considered. Inspection sensitivity levels were of interest for flaws such as porosity, delamination or disbonds, misaligned plies, resin-rich areas and core matrix cracking. From past experience at P&WA and other work reported, a summary was compiled that identified inspection methods best suited for particular defects (Table 4-XV).

TABLE 4-XV

CANDIDATE INSPECTION TECHNIQUES

<u>Defect</u>	<u>NDI Techniques for Nonmetallic Composites</u>
Porosity	low voltage X-ray, ultrasonics, eddy current
Delamination/disbonds	ultrasonics, holography, acoustic emission
Misaligned plys	low voltage X-ray
Resin-rich areas	low voltage X-ray
Cracking	low voltage X-ray, acoustic emission, eddy current

Holography, eddy current and acoustic emission were eliminated as multipurpose flaw detection inspection techniques. Holography was not chosen for evaluation because of its limited sensitivity to small defects located more than 5 mm (0.2 in.) below the surface. The variation in vane thickness and occasional transition of material density along the chordal and spanwise direction of the airfoil precluded the effective use of state-of-the-art eddy current techniques for locating cracks and delamination. Acoustic emission was not selected due to the considerable effort required to correlate output signals to size, location and flaw type.

Ultrasonic "C" scan and low voltage radiography appeared to offer the most promise and were selected for further evaluation of intentionally flawed vanes. Ultrasonic "C" scan has been proven effective for detecting porosity and disbond/delamination. For the composite fan exit guide vane, pulse-echo ultrasonic "C" scan inspection was not considered since the presence of fiberglass, graphite and polyurethane interfaces would tend to scatter pulsed sound and result in interpretation difficulty. However, through transmission ultrasonic "C" scan techniques are not significantly influenced by extraneous reflections. This ultrasonic technique and low voltage radiography were the final candidates selected to evaluate all four types of intentionally flawed vanes.

Prior to ultrasonic and radiographic inspection, vanes were visually inspected. Visual inspection revealed a number of intentionally placed flaws which were close to the vane surface. Observation of Composites Horizons' graphite NDI vane revealed what appeared to be the 2.54 cm (1 in.) diameter resin-rich area on the concave surface and porosity at the trailing edge (Figure 4-15). Inspection of the Composites Horizons' hybrid glass shell/graphite core vane also revealed the resin-rich area on the concave surface and the presence of two teflon inserts between

the core and shell at either end of the vane as well as a density variation at the trailing edge (Figure 4-16). Visual examination of the all graphite TRW vane showed a tool line 1.27 cm (0.5 in.) from and parallel to the trailing edge (Figure 4-17). This was caused by an insert used to shape the trailing edge during molding. The effect was visible on concave and convex vane surfaces in both uncoated and polyurethane coated condition. Foreign material, represented by teflon to promote disbonds of 0.64 cm (0.25 in.) and 1.27 cm (0.5 in.) diameter at the shell to polyurethane coating, was observed on the convex surface. Visual inspection of the hybrid glass shell/graphite core vane showed essentially all of the shell and shell to core located contaminants (Figure 4-18). As anticipated, material contaminants and deviations are more visible in the hybrid glass shell/ graphite core material than in the all graphite part. Several problems were encountered by TRW during fabrication of NDI vanes. The spacing and size of intentional defects at the trailing edge did not provide sufficient sound area around each flaw. Consequently, the trailing edge area not only had intentional flaws but also experienced disbonds in regions surrounding intentional flaws. Tap testing at the trailing edge confirmed gross disbonding. NDI inspection of this vane provided questionable results due to the overlap of flaws.

Immersion ultrasonic "C" scan inspection was conducted using a through transmission system with a 1.27 cm (0.5 in.) diameter, 2.0 MHz focused transmitter and a 2.54 cm (1.0 in.) diameter, 2.0 MHz receiver. The part was scanned in the spanwise direction in 1.52 mm (0.06 in.) increments at 30.5 cm/sec (1 ft/sec.). The transmitting crystal was maintained 2 inches from the concave surface of the vane and held reasonably normal ($+5^{\circ}$) to the vane for the more critical midchord to trailing edge section; receiver crystal was 1.27 cm (0.5 in.) from the vane. Signal threshold was varied from 8 to 28 db relative to water path attenuation between transducers. The most definitive "C" scan display obtained identified the teflon insert between the core and shell and core matrix cracking of the all graphite vane (Figure 4-19). This technique did not reveal any of the other intentional flaws in Composites Horizons' fabricated vanes. It is expected that some improvement in sensitivity could be achieved by maintaining the crystals more normal to the inspection surface. However, the lens effects of the concave and convex vane surfaces and changing thickness from midchord to trailing edge will result in continuing changes in focal point and attenuation and thereby limit inspection sensitivity. Inspection of the remaining three vanes showed similar limitations in signal printout. To optimize this system for inspection would require a controlled mechanical procedure to maintain transmitting and receiving crystals normal to and equidistant from inspection surfaces. Time and funding were not available to pursue this approach. Primary emphasis during the inspection program was, therefore, placed on low voltage X-ray; all of the standard and fatigue tested vanes were inspected using this technique.

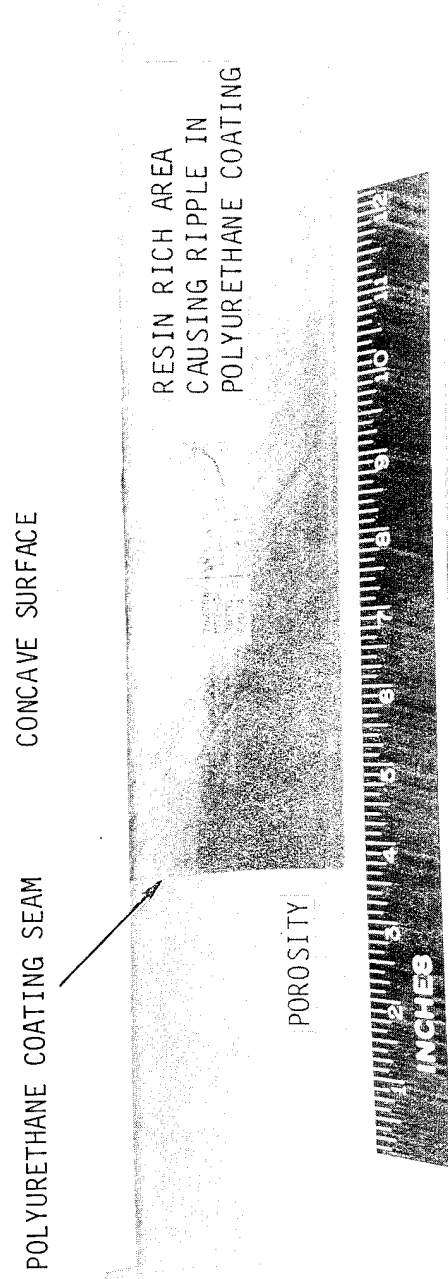
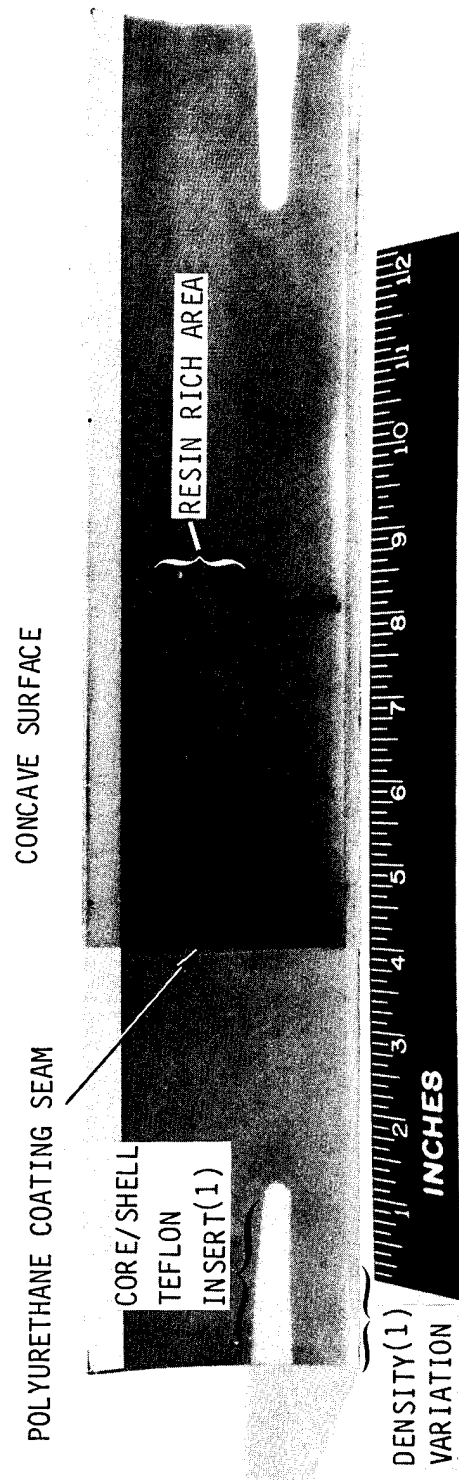


Figure 4-15 Photograph of Nondestructive Evaluation Standard Vane
Graphite Shell Graphite Core/Epoxy Composites Horizons;
S/N 4



(1) EFFECT VISIBLE AT BOTH ENDS OF VANE

Figure 4-16 Photograph of Nondestructive Evaluation Standard Vane;
Fiberglass Shell Graphite Core/Epoxy Composites
Horizons; SN 01

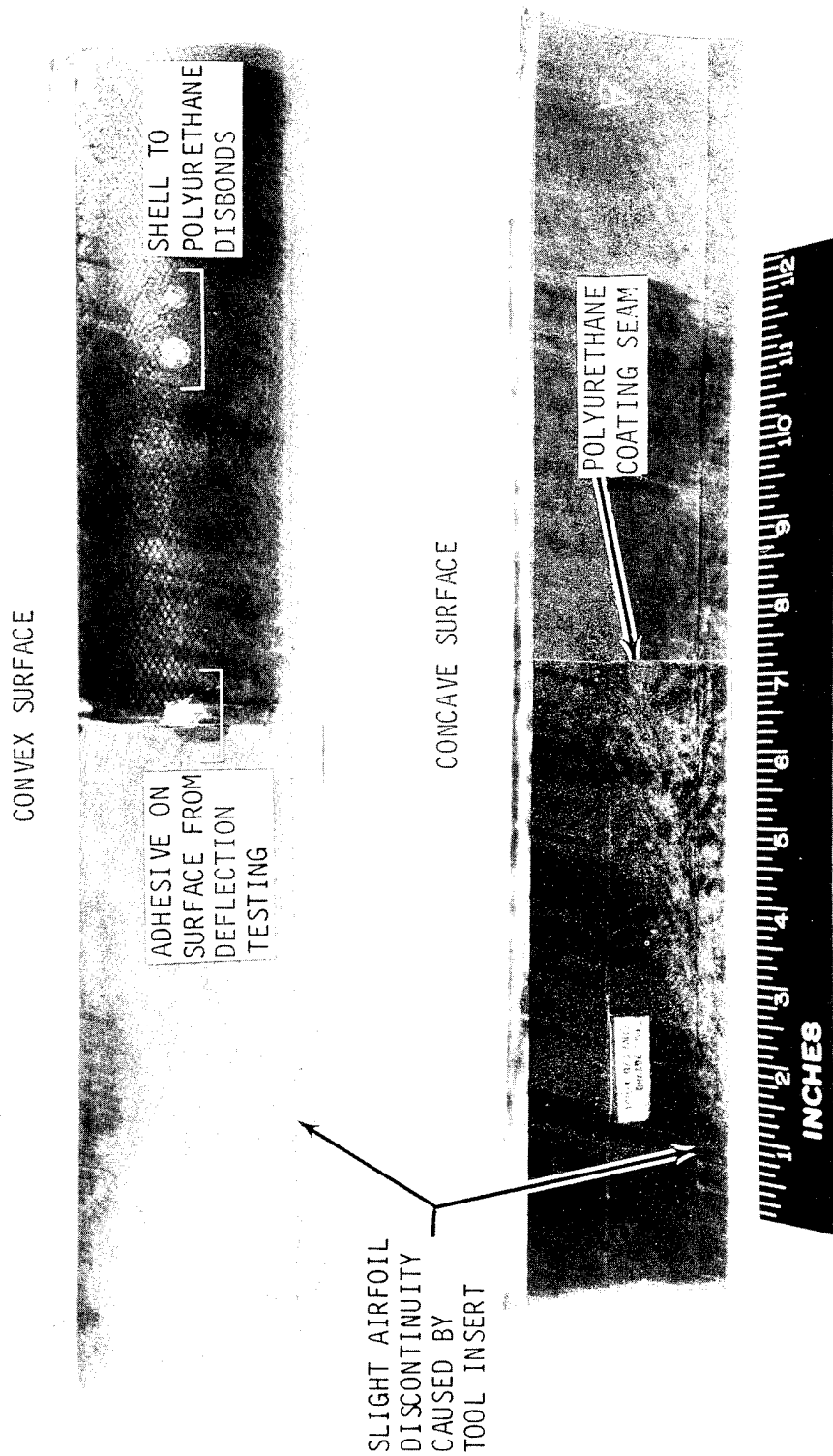


Figure 4-17 Photograph of Nondestructive Evaluation Standard Vane;
Graphite Shell Graphite Core/Epoxy - TRW S/N 1-001

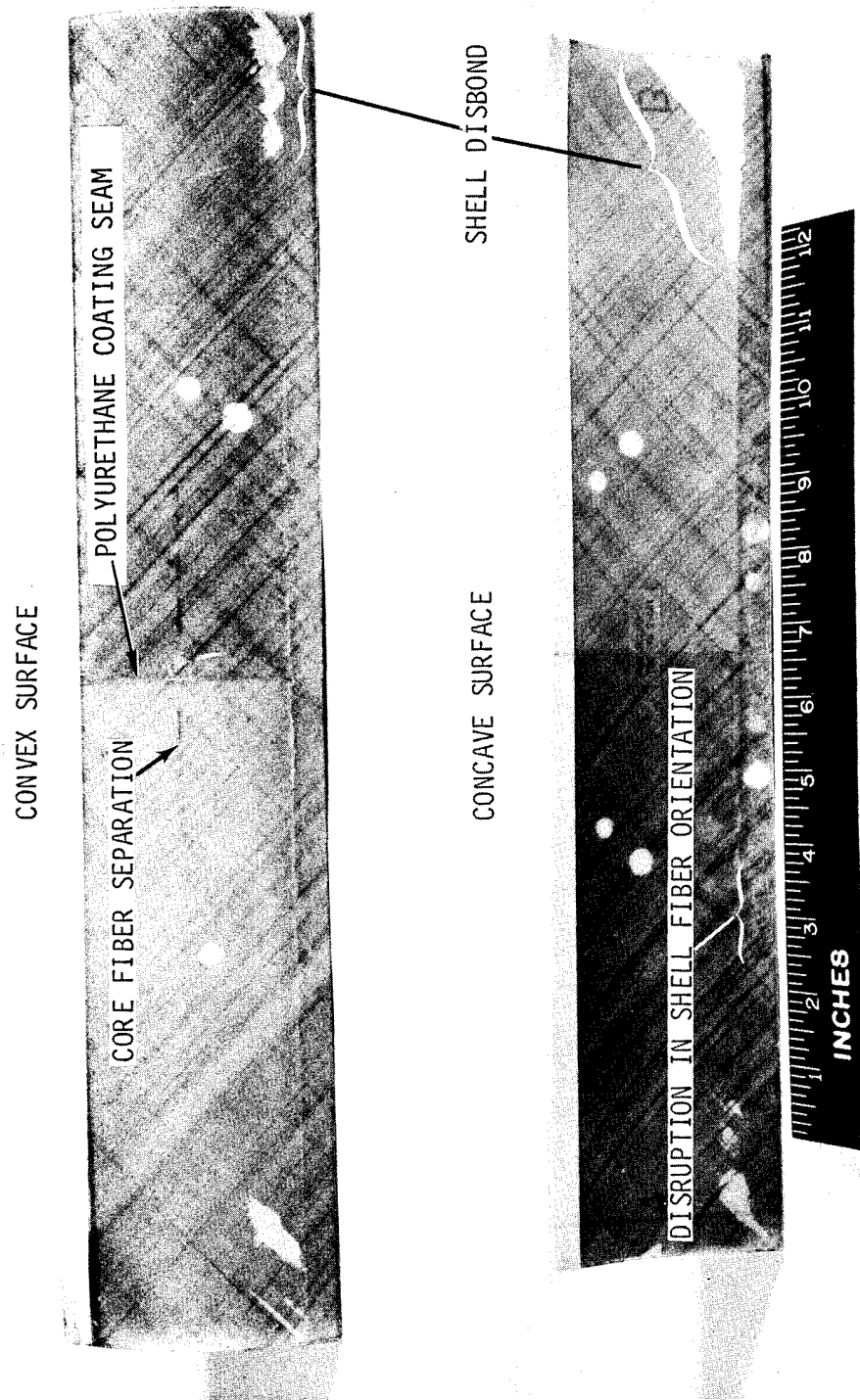


Figure 4-18 Photograph of Nondestructive Evaluation Standard Vane;
Fiberglass Shell Graphite Core/Epoxy - TRW S/N 2-001

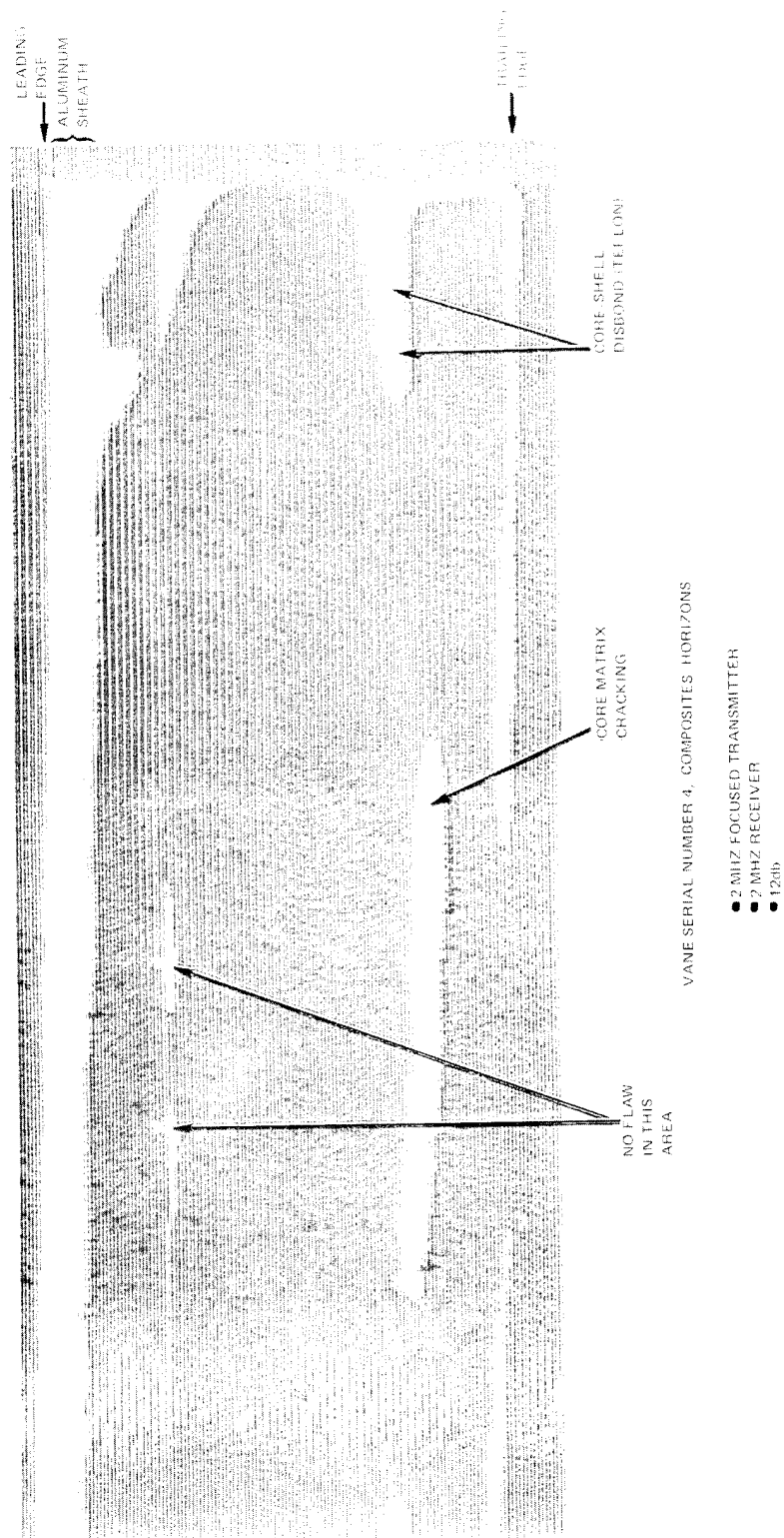


Figure 4-19 *Ultrasound "C" Scan of Graphite/Epoxy Intentionally Flawed Vane (Polyurethane Coated Section)*

Radiographic inspection was performed with an X-ray tube voltage of 16 KV and a current of 3 milliamperes using Kodak "M" film with no lead screen and exposed 3 to 5 minutes; target to film distance was 21 inches. Radiographic inspection of the four NDI vanes revealed a considerable number of the intentionally placed defects (Figures 4-20, 4-21, 4-22, and 4-23). Evaluation of the Composites Horizons' all graphite part using a combination of visual and x-ray examination revealed that eight of the eleven known defects were detectable; for the hybrid glass shell/graphite core vane nine of eleven variations were detectable. Examination of TRW all graphite parts by visual inspection and radiography revealed five of nine flaws were detectable; for the hybrid glass shell/graphite core vane eight of ten types of flaws were detectable. Table 4-XVI summarizes flaw materials used, flaw size and detection capability by low voltage X-ray and visual examination for both all graphite and hybrid glass graphite vanes. In conclusion the combination of visual inspection and low voltage radiography was effective in detecting most of the intentional and unintentionally introduced flaws in NDI vanes.

4.3.3 Microscopic Examination

Microstructure examination of pretest vanes was performed to evaluate porosity, ply lay-up, fiber/resin homogeneity and fiber continuity at trailing and leading edges of the airfoil. Vanes were sectioned for microscopic examination by removing a 0.95 cm (0.375 in.) section from the end of the vane. Vanes were sectioned again after fatigue test in a region away from the failure site to confirm earlier microscopic examination.

Several microstructural differences were noted when comparing TRW fabricated parts to Composites Horizons parts. The most pronounced difference was noted in the level of porosity. Composites Horizons parts as typified by Figures 4-24 and 4-25 displayed no significant porosity whereas TRW parts (Figures 4-26 and 4-27) showed considerable porosity which was more intense at the leading edge than the trailing edge. This variation was expected since Composites Horizons had more fabrication experience than TRW prior to the subject program. Fatigue test results which are reported in Section 5 indicated no differences in durability between vanes fabricated by either vendor. Another variation in fabrication detail was visible in trailing edge structure. Composites Horizons vanes incorporated a total of either four layers of graphite shell fiber or two layers of glass cloth all of which were wrapped around the trailing edge (Figures 4-24 and 4-25). During the molding process several of the layers on some graphite shell parts and both layers on the glass cloth part were partially exuded out of the trailing edge mold parting line. Apparently this partial loss of fiber material did not affect fatigue properties. TRW chose to avoid this potential problem by placing a thin 0.05 mm (0.002 inch) trailing edge shaped aluminum sleeve at the parting line in the mold cavity to prevent fiber from being forced out of the mold at that location during pressing. The TRW

parts were fabricated with four graphite or two fiberglass shell ply layers; however, the two innermost graphite ply layers were cut at the trailing edge prior to lay-up to prevent fiber kinking and fabrication problems which might occur in bending the shell around the trailing edge radius. Differences were also observed in position of shell fiber termination at the rear edge of the leading edge aluminum shroud. Microsections of four typical parts indicated a variation of fiber termination position. This region of the vane is not highly stressed and fiber position did not appear to be critical. A summary of these differences is presented below (Table 4-XVII).

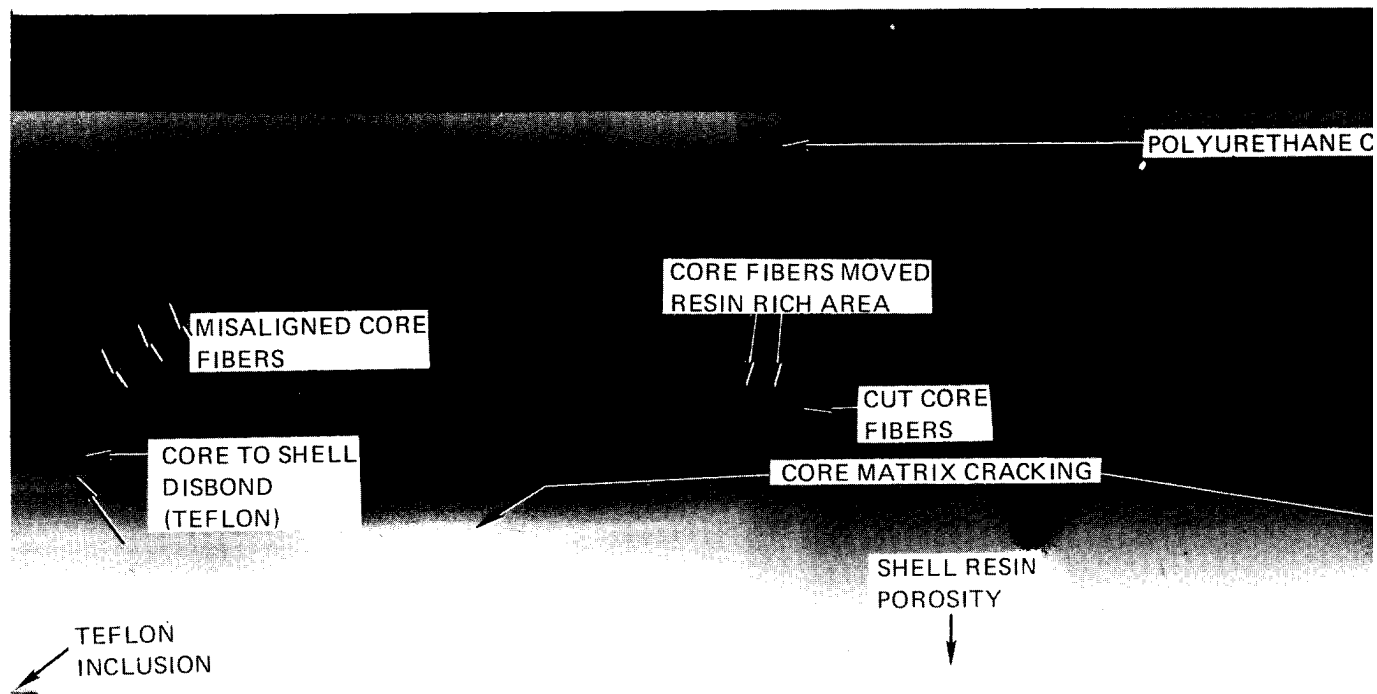
High magnification documentation is presented for each of the four vane configurations at the shell to core interface zone. Details visible are 1) fibershape in the vane shell and core, 2) resin/fiber distribution in the shell, 3) the transition zone of shell to core and 4) shell to polyurethane film interface (Figures 4-28 and 4-29).

TABLE 4-XVII

MICROSTRUCTURAL FEATURES OF VANES

	<u>Composites Horizons</u>		<u>TRW</u>	
	<u>All Graphite</u>	<u>Glass-Graphite</u>	<u>All Graphite</u>	<u>Glass-Graphite</u>
Porosity	Nil	Nil	Light to Heavy ⁽¹⁾	
Shell Fiber Continuity at Trailing Edge	Good	Fair	Good	Good
Shell Thickness Control	Good	Good	Good	Fair
Shell Blending at Leading Edge Sheath	Good	Good	Good	Fair
Fiber Homogeneity	Good	Good	Good	Good

⁽¹⁾ Porosity more concentrated in early fabricated vanes and at ends of part.



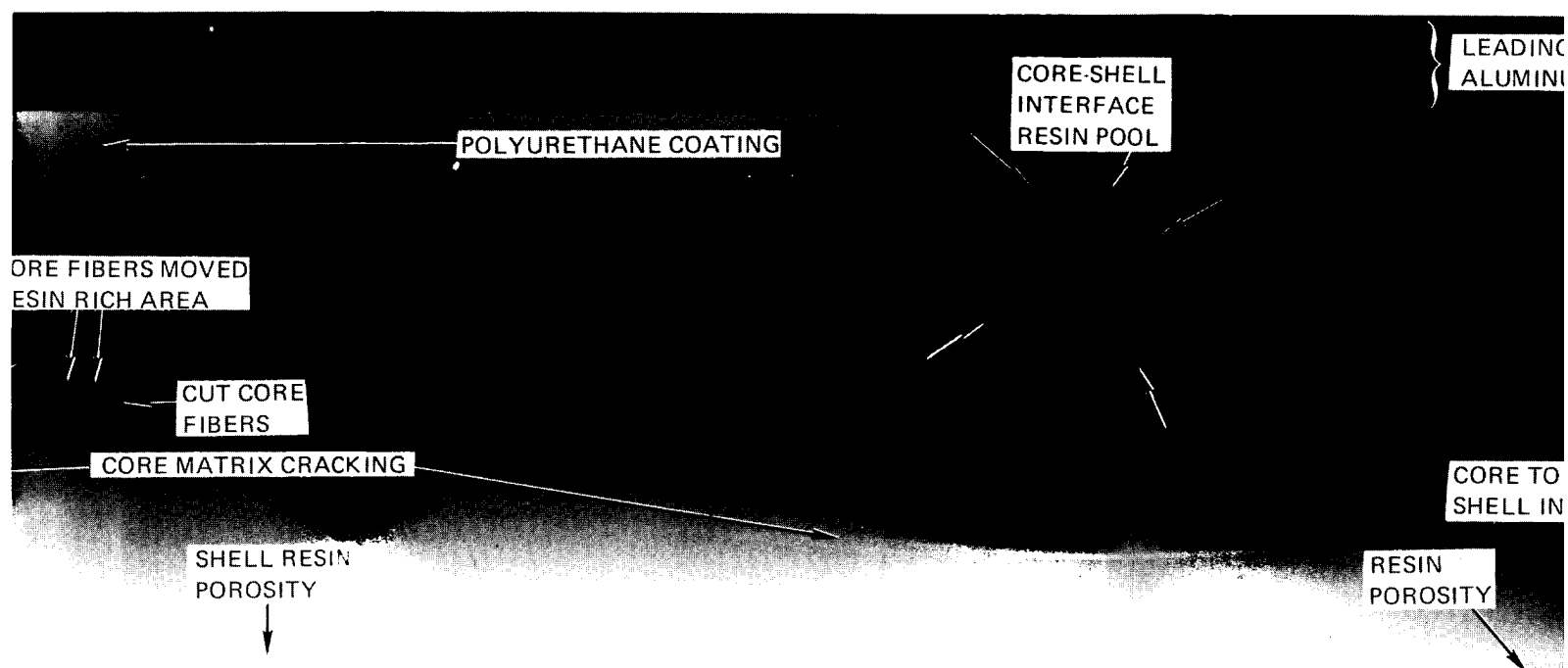


Figure 4-20

Print from Radiograph of Composites Ho
Intentionally Flawed Graphite/Epoxy ND
4)

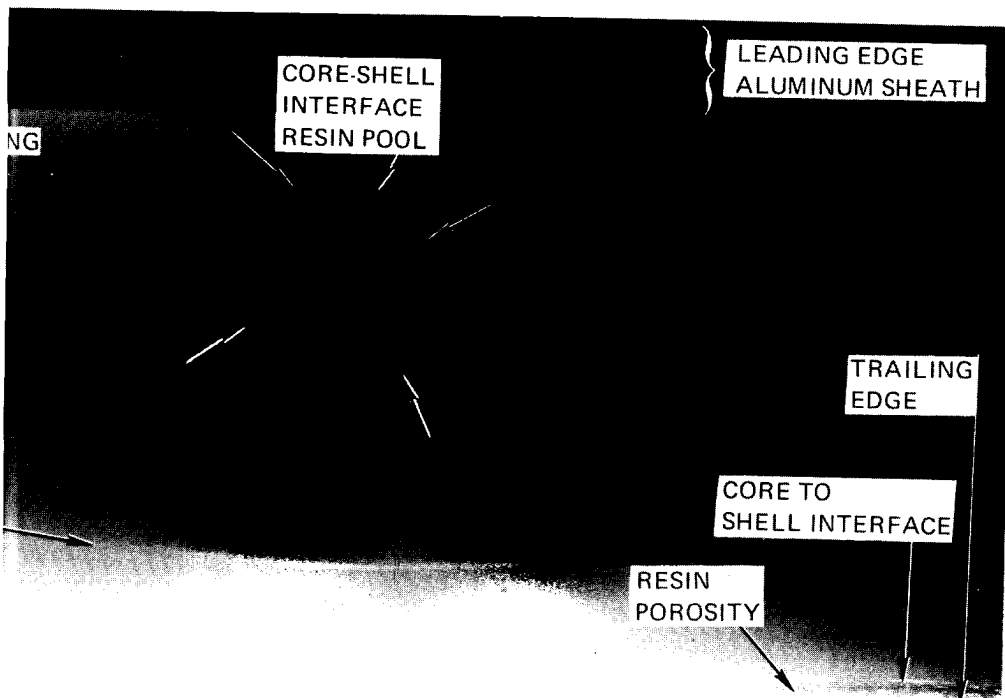
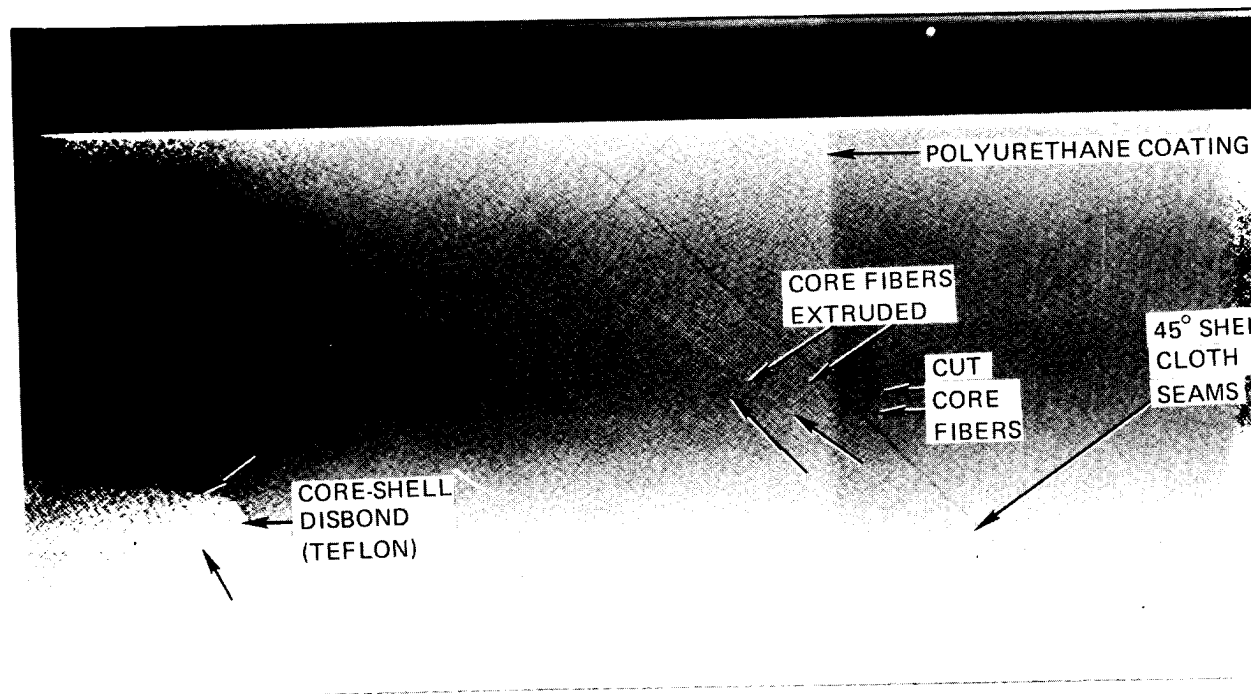


Figure 4-20 Print from Radiograph of Composites Horizons
 Intentionally Flawed Graphite/Epoxy NDE Vane (Vane No.
 4)



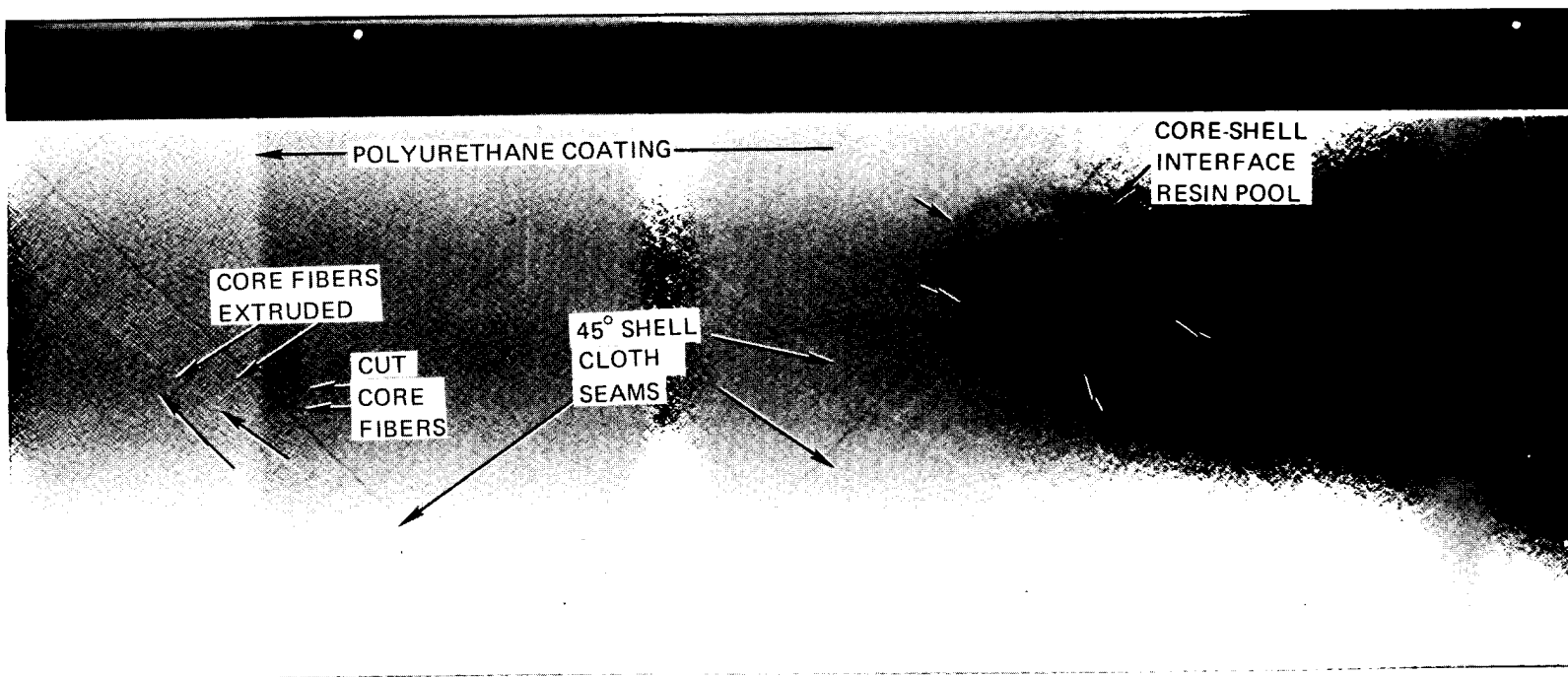


Figure 4-21

Print from Radiograph of
Intentionally Flawed Hy
Core/Epoxy NDE Vane (Va

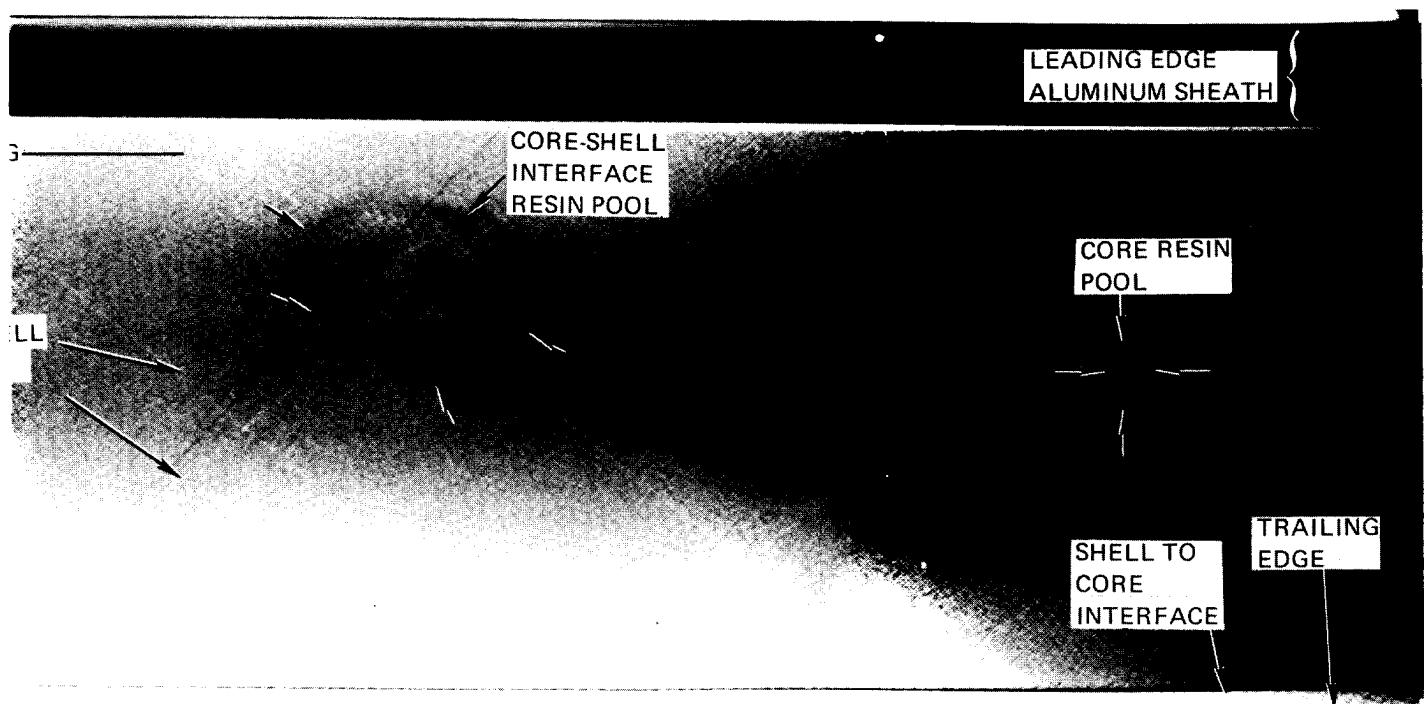


Figure 4-21 *Print from Radiograph of Composites Horizons
Intentionally Flawed Hybrid Glass Shell Graphite
Core/Epoxy NDE Vane (Vane No. 1)*

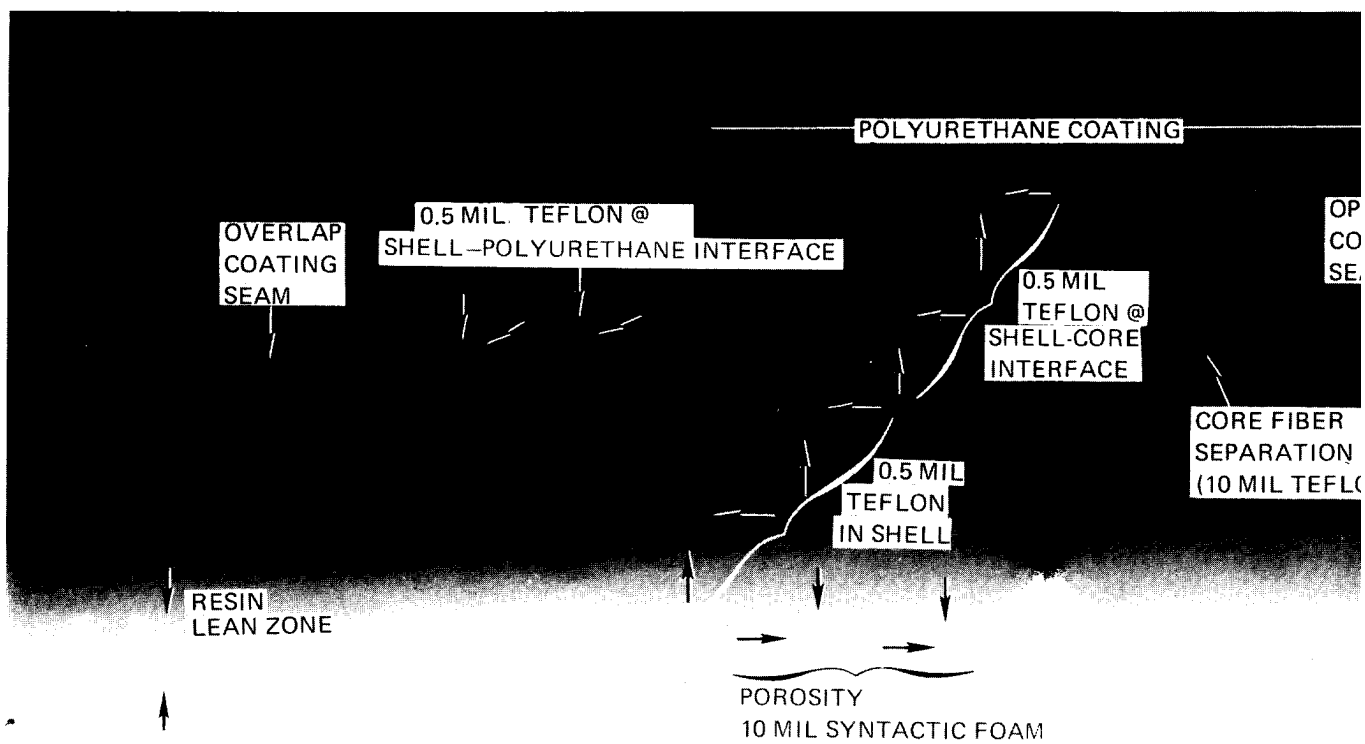




Figure 4-22

Print from Radiograph of TRW Intentionally Flawed Graphite/Epoxy NDI Vane (Vane No. 1-001)

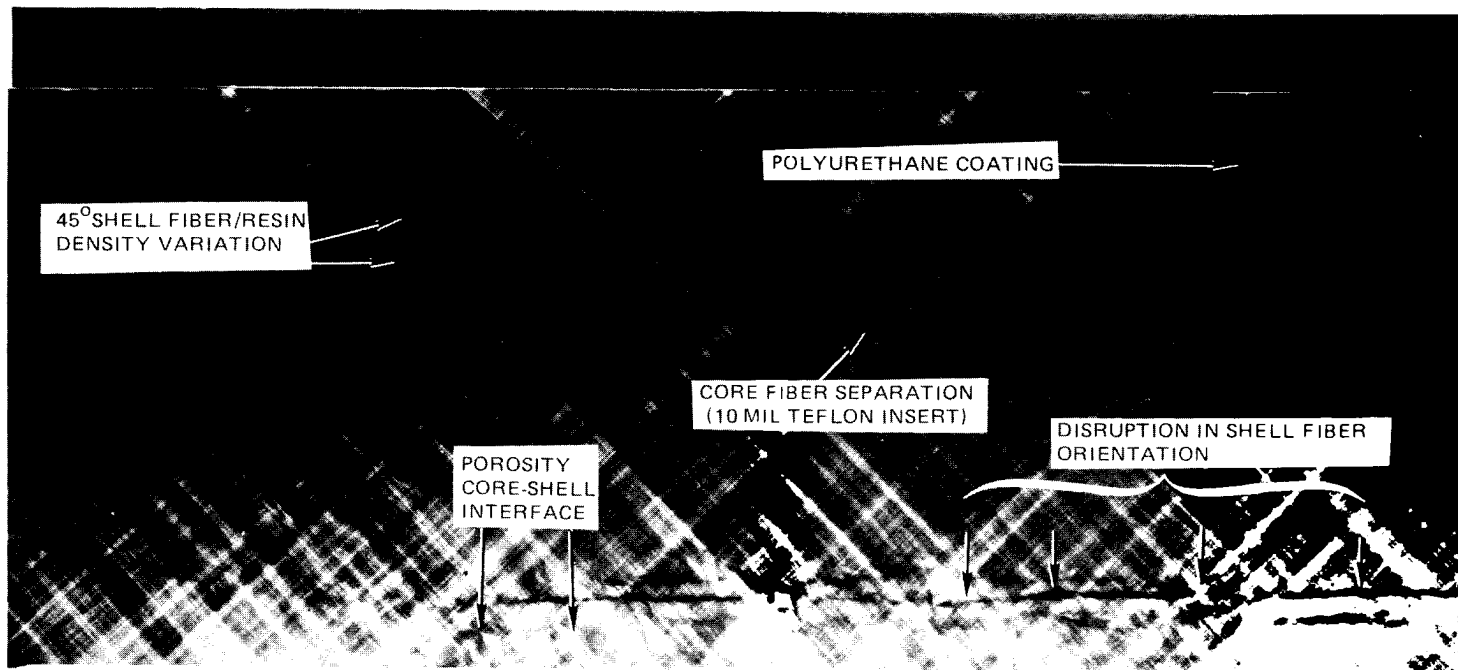


Figure 4-23

Print from
Hybrid Glas
No. 2-001)

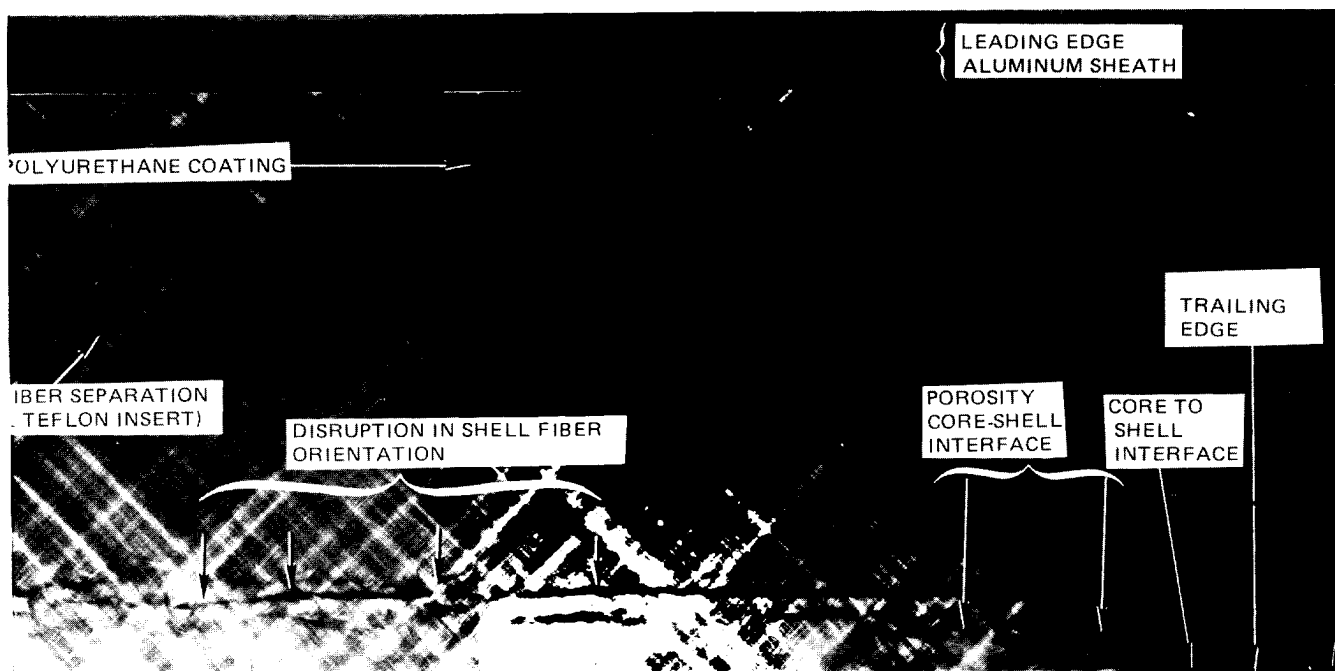


Figure 4-23

*Print from Radiograph of TRW Intentionally Flawed
Hybrid Glass-Shell Graphite Core/Epoxy NDE Vane (Vane
No. 2-001)*

TABLE 4-XVI

DETECTABILITY OF FLAWS IN NDI VANES

	Flaw Material/Size	Graphite Vane		Glass-Graphite Vane	
		Radio-graphy	Visual	Radio-graphy	Visual
<u>COMPOSITES HORIZONS' VANES</u>					
<u>Core Defects</u>					
1. Matrix Cracking	Mold Release/0.25 mm	Yes	No	No	No
2. Fibers Cut	- /0.25 mm	Yes	No	Yes	No
3. Resin Pool	Neat Resin/1.2 cm	No	No	Yes	No
4. Misaligned Fibers		Yes	No	Yes	No
<u>Core/Shell Defects</u>					
5. Disbond	Teflon/2.5 cm	Yes	No	Yes	Yes
6. Resin Pool	Neat Resin/2.5 cm	Yes	Yes	Yes	Yes
<u>Shell Defects</u>					
7. Ply Gap		No	No	Yes	Yes
8. Porosity	Syntactic Foam	Yes	Yes	No	No
9. Fiber Misalignment		No	No	Yes	Yes
10. Trailing Edge Porosity /Inclusion		Yes	Yes	Yes	Yes
11. Polyurethane Coating Transition		Yes	Yes	Yes	Yes
<u>TRW VANES</u>					
<u>Core Defects</u>					
1. Matrix Cracking	Teflon/0.25 mm	Yes	No	Yes	No
2. Resin Pool	Neat Resin/0.13 mm	No	No	No	No
<u>Core/Shell Defects</u>					
3. Disbond	Teflon/0.13 mm	Yes	No	No	Yes
4. Resin Pool	Neat Resin/0.13 mm	No	No	Possibly	Yes
5. Trailing Edge Porosity	Syntactic Foam/ 0.25 mm thick	Yes	No	Yes	Yes
<u>Shell Defects</u>					
6. Delamination	Teflon/0.013 mm	Yes	Yes	No	Yes
7. Delamination at Polyurethane Interface	Teflon/0.013 mm	Yes	Yes	No	Yes
<u>Unintentional Flaws</u>					
8. Kinked Shell Fiber		No	No	Yes	Yes
9. Delamination at core/shell interface		-	-	Yes ⁽¹⁾	Yes ⁽¹⁾
10. Uniform fine porosity throughout core		No	No	No	No

(1) Tap test and changing surface contour

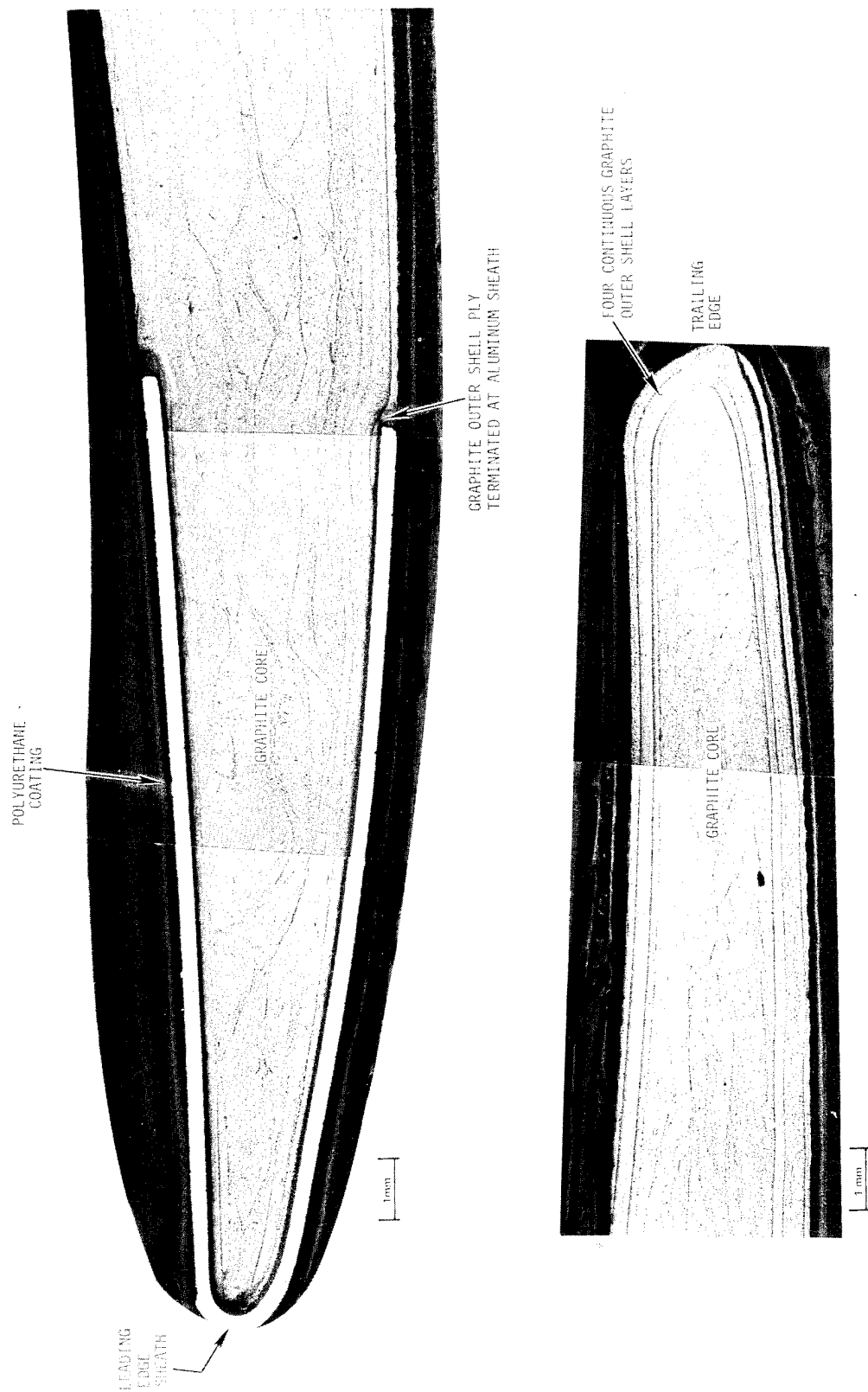


Figure 4-24 Photomicrograph of Typical Cross Section of Composites
Horizons Fabricated Glass Shell Graphite Core/Epoxy Fan
Exit Guide Vane

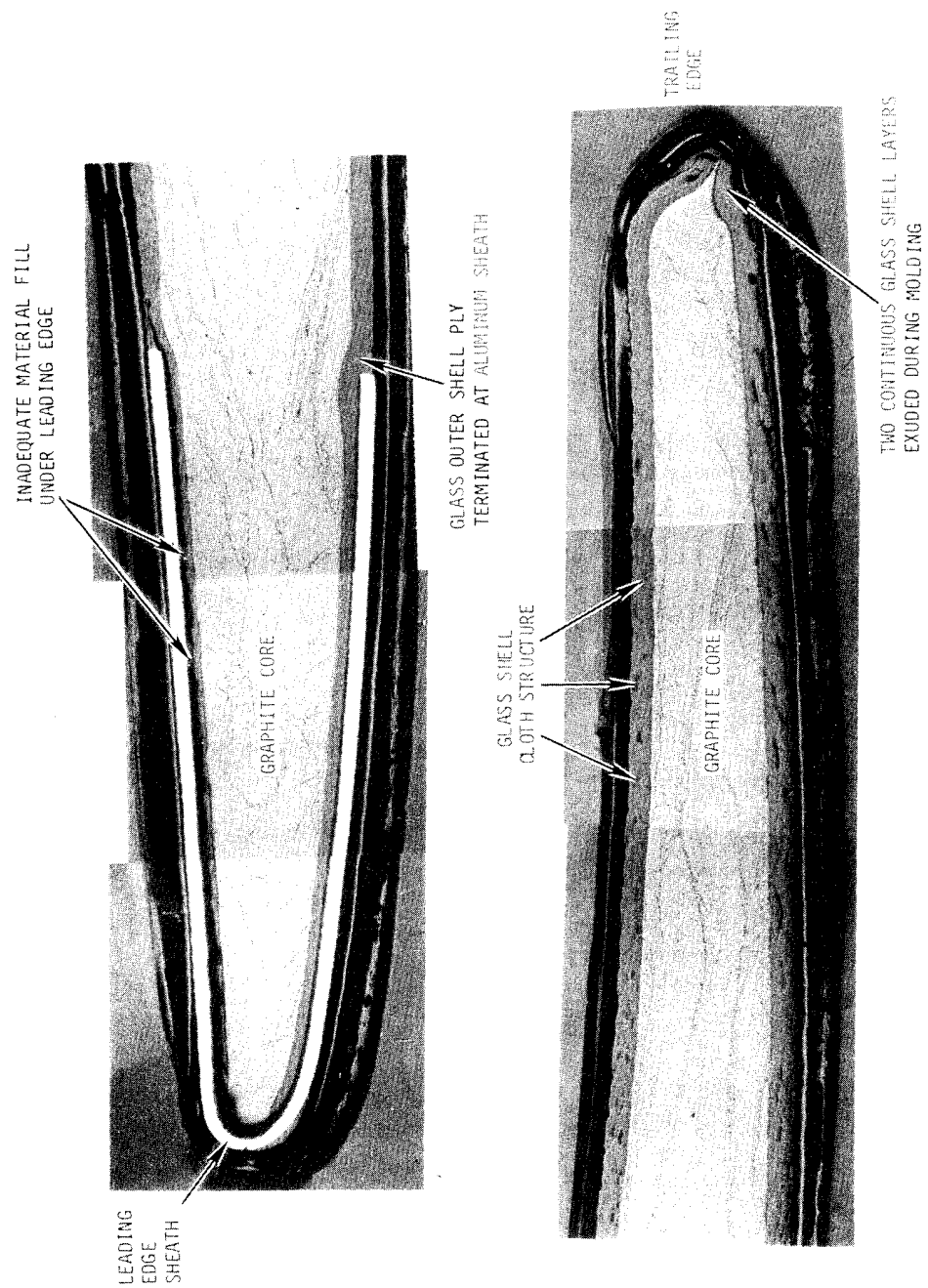


Figure 4-25 Photomicrograph of Typical Cross Section of Composites
Horizons Fabricated Glass Shell Graphite Core/Epoxy Fan
Exit Guide Vane

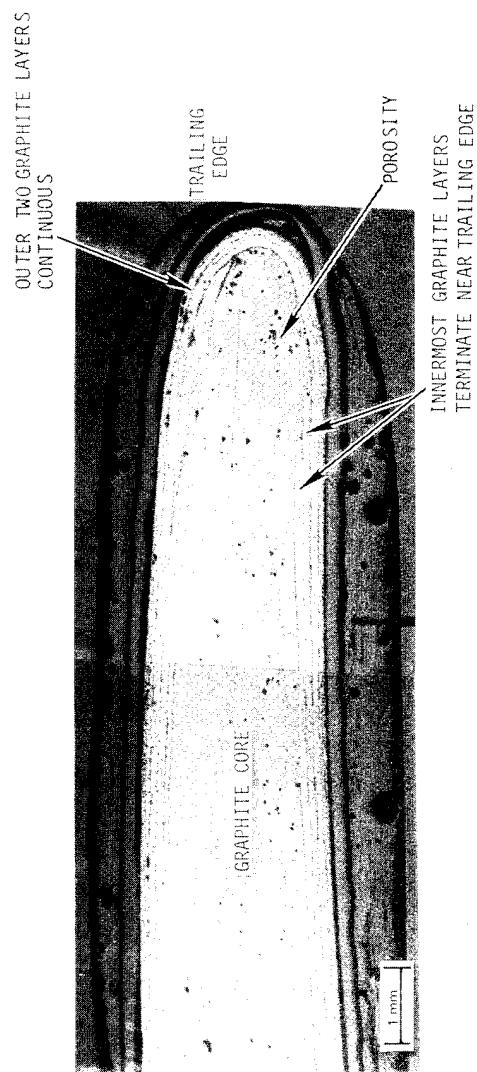
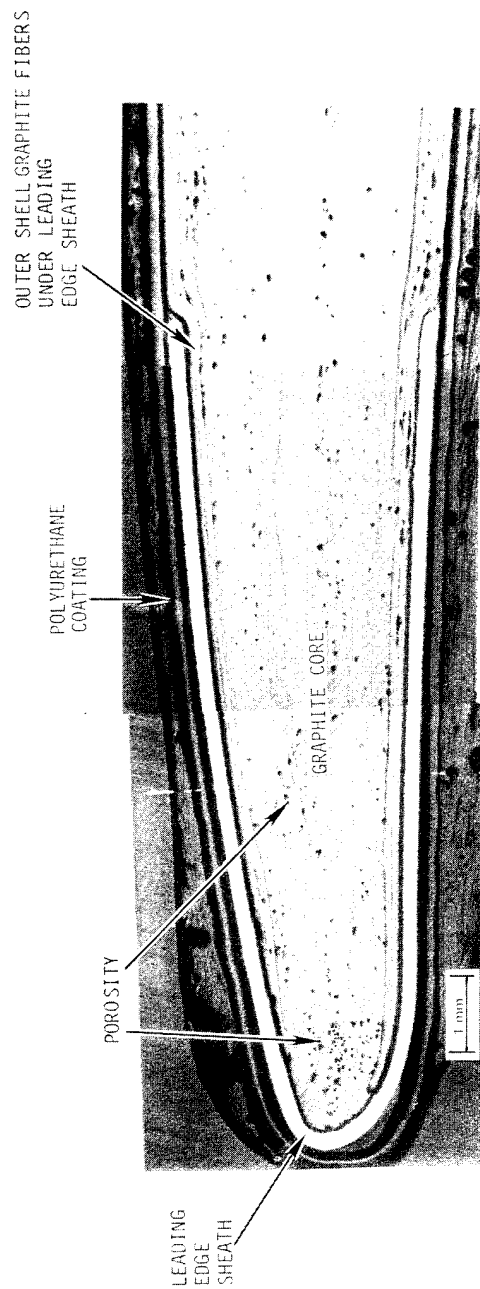


Figure 4-26 Photomicrograph of Typical Cross Section of TRW
Fabricated Graphite Shell Graphite Core/Epoxy Fan Exit
Guide Vane

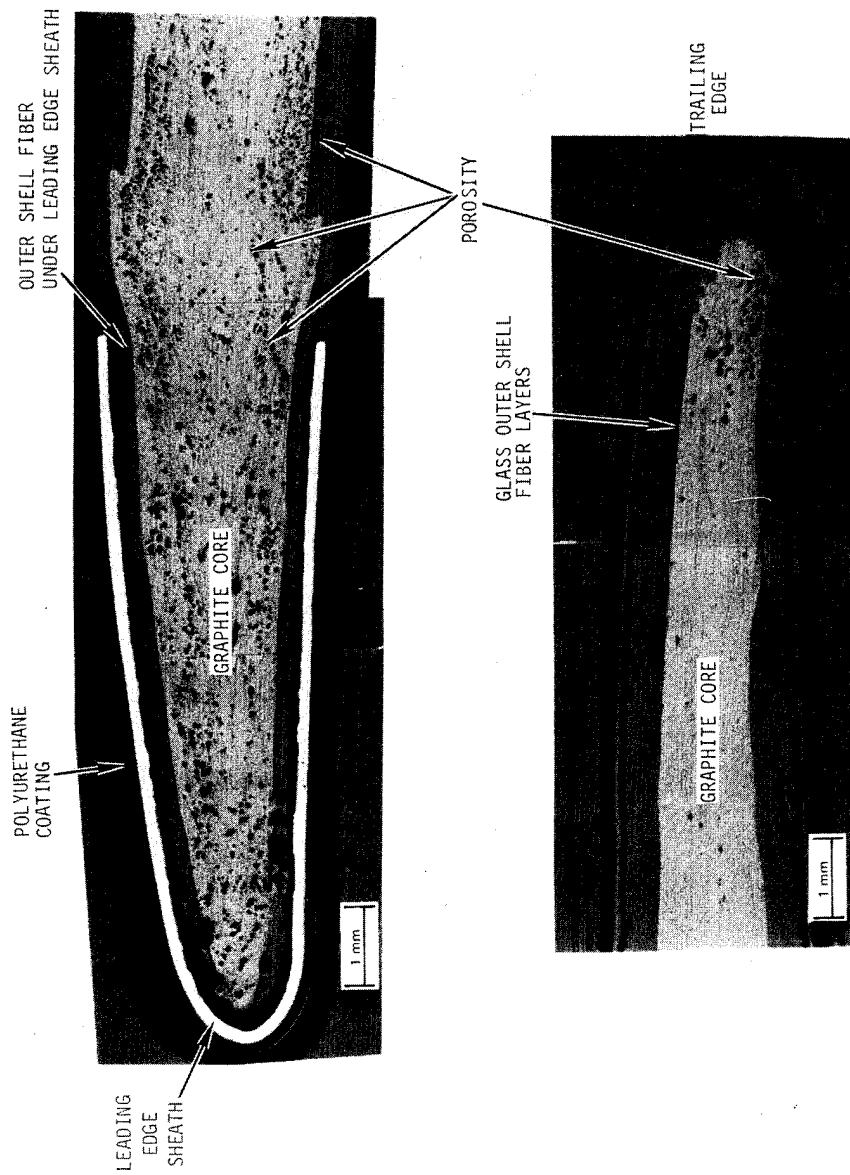


Figure 4-27 Photomicrograph of Typical Cross Section of TRW
Fabricated Glass Shell Graphite Core/Epoxy Fan Exit
Guide Vane

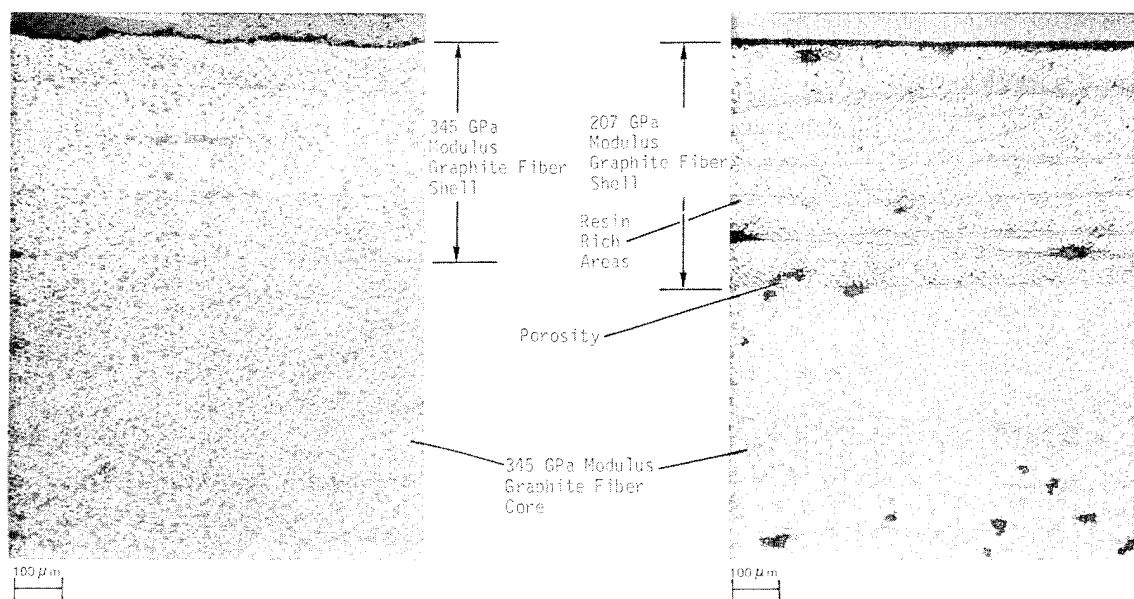


Figure 4-28 Photomicrographs of Graphite/Epoxy Fan Exit Guide Vanes. Comparison of Shell and Core Microstructure at Typical Transverse Cross-Section.

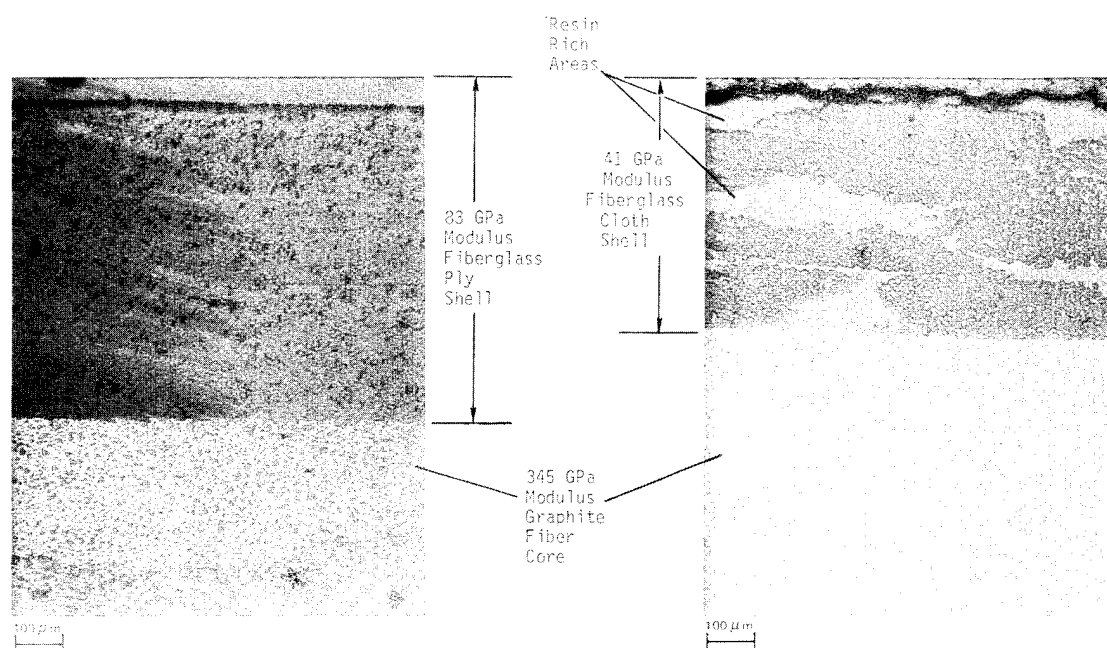


Figure 4-29 Photomicrographs of Fiberglass Shell-Graphite Core/Epoxy Fan Exit Guide Vane. Comparison of Shell and Core Microstructure at Typical Transverse Cross-Section.

5.0 RESULTS AND DISCUSSION

5.1 VANE BENCH TESTING

5.1.1 Test Approach

In addition to nondestructive inspection of the intentionally defective and sound vanes, each sound vane was tested sequentially in both static bending and torsion to determine part stiffness and processing quality. Subsequent to stiffness testing, each part was either environmentally conditioned or retained in the as-fabricated condition for fatigue testing. For the twenty vanes of four different material/ply lay-ups, three of each group of five were tested in the as-fabricated condition and two of five were tested warm 60°C (140°F) and wet (0.6-0.8 weight percent moisture). Post-test evaluation consisted of visual inspection, nondestructive evaluation and microscopic examination.

5.1.2 Static Mechanical Tests

To determine bending springrate, each vane was supported on the convex surface by two contoured knife edges located 39.9 cm (15.7 in.) apart. A uniform pressure load was applied to a 37.3 cm (14.7 in.) span of the vane concave surface with an air bladder (Figure 5-1). Each vane was loaded in 6.5 kPa (1 psig) increments over the range of 13 kPa (2 psig) to 40 kPa (6 psig). Dial indicators were used to measure vane midspan deflection at LE, midchord and TE. One vane of each of the four types was instrumented with a radially (span direction) oriented 1.57 mm (0.062 in.) grid strain gage on the midspan convex surface, 2.5 mm (0.100 in.) forward of the TE. One each of the two types of TRW vanes had a total of fourteen (14) strain gages placed on the airfoil concave surface as shown in Figure 5-2. Average bending stiffness of graphite core/graphite shell vanes varied between 0.404-0.421 MN/M (2305-2403 lb/in) and was 5-10 percent higher than graphite core/glass shell vanes (Table 5-I). Vane bending stiffness for all four configurations exceeded established requirements.

Trailing edge strain measurements made during test in the bending springrate rig were used to determine the static strain level to be set for fatigue testing. Vanes tested in an earlier program had been similarly strain gaged, springrate and engine tested, thereby providing a calibrated static test. Measured trailing edge static strain of $-1750\mu\epsilon$ was selected as typical average engine level strain for all four vane configurations.

Torsion springrate was determined by clamping the vane OD end into a fixed support that was contoured to match the vane airfoil shape. A torqueing bar was fixtured via a contoured clamp at the opposite end of the vane (Figure 5-3). Increments of 2.28 kg (5 lbs) dead weight loads were applied via a pulley system to each end of the 0.30 m (12 in.) torque bar for a total torque of 6.8 M-N (60 inch-lb). Tangential deflections at both ends of the torqueing bar were measured with dial indicators. Torsional stiffness of the four vane material/design confi-

gurations spanned the range from 0.99 to 2.38 M.N/deg (8.7 to 21.1 in. lb/deg.). Comparison of the bending and torsion stiffness data for the most severely defected NDI vane (S/N 2-001) to sound companion vanes of the same material/configuration showed these tests to have no merit in detecting flaws introduced in this program.

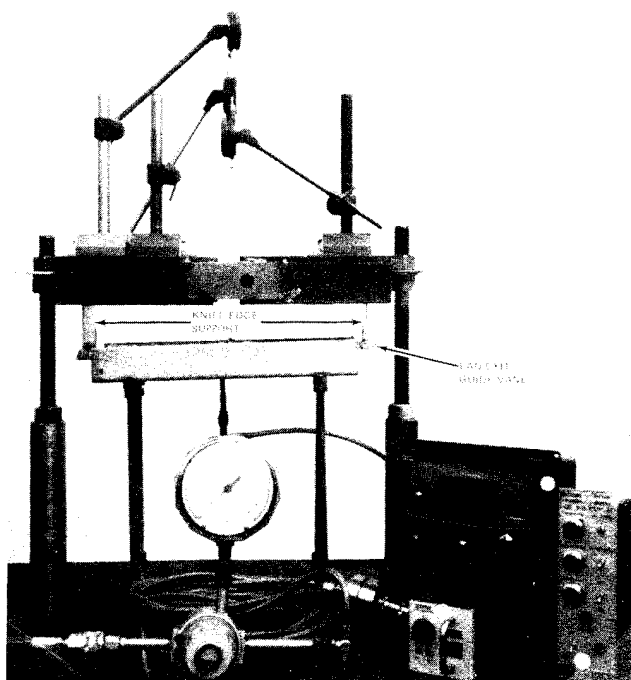
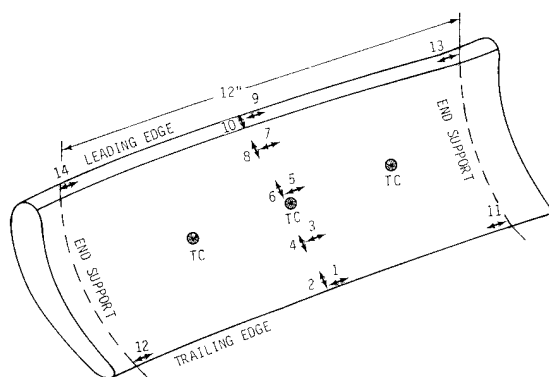


Figure 5-1 Vane Bending Spring Rate Fixture for Application of Bending Load to Vane.



NOTES:

- I. CONTROL GAGE AT LOCATION 1 ON VANE CONCAVE SURFACE
- II. GAGE LOCATIONS 1 THROUGH 10 USED TO DESCRIBE CHORDWISE STRAIN DISTRIBUTION ON CONCAVE SURFACE
- III. BACK-TO-BACK GAGES AT LOCATIONS 11 THROUGH 14 USED TO CHECK STRAINS AT END SUPPORTS
- IV. THERMOCOUPLE ON CONCAVE AND CONVEX SIDES

Figure 5-2 Fan Exit Guide Vane Strain Gage and Thermocouple Locations

TABLE 5-I

VANE BENDING STIFFNESS TEST RESULTS

	Vane Serial Number	K _{Torsion} M-N/Deg (in. lb/deg)	K _{Bend} MN/M (lb/in)
<u>COMPOSITES HORIZONS</u>			
F-5A Core			
F-5A Shell (+35°)			
Tool Trial		2.56 (22.7)	0.392 (2240)
NDI Vane	4	2.16 (19.1)	0.388 (2216)
Fatigue Test Vanes	30	2.27 (20.1)	0.402 (2301)
	34	2.45 (21.7)	0.403 (2301)
	36	2.30 (20.4)	0.398 (2276)
	32	2.46 (21.8)	0.414 (2365)
	35	2.49 (22.1)	0.426 (2433)
	Avg.	2.38 (21.1)	0.404 (2305)
F-5A Core			
S-Glass Cloth Shell (+45°)			
NDI Vane	1	1.05 (9.3)	0.360 (2055)
Fatigue Test Vanes	11	0.98 (8.7)	0.363 (2075)
	9	0.97 (8.6)	0.370 (2117)
	12	1.02 (9.0)	0.369 (2106)
	7	0.99 (8.8)	0.374 (2138)
	8	0.99 (8.8)	0.378 (2160)
	Avg.	0.99 (8.7)	0.369 (2109)
<u>TRW</u>			
F-5A Core			
AS-2 Shell (+30°)			
Tool Trial	1-00A	1.51 (13.4)	0.346 (1978)
NDI Vane	1-001	1.61 (14.3)	0.405 (2313)
Fatigue Test Vanes	1-003	1.75 (15.5)	0.414 (2365)
	1-004	1.73 (15.3)	0.394 (2252)
	1-008	1.98 (17.5)	0.446 (2550)
	1-006	1.84 (16.3)	0.431 (2461)
	1-011	2.02 (17.9)	0.507 (2899)
	Avg.	1.77 (15.7)	0.421 (2403)
F-5A Core			
S-Glass Ply Shell (+45°)			
NDI Vane	2-001	1.49 (13.2)	0.384 (2194)
Fatigue Test Vanes	2-002	1.29 (11.4)	0.382 (2182)
	2-003	1.24 (11.0)	0.353 (2016)
	2-007	1.50 (13.3)	0.444 (2535)
	2-005	1.44 (12.8)	0.415 (2370)
	2-008	1.45 (12.9)	0.403 (2301)
	Avg.	1.41 (12.5)	0.397 (2268)

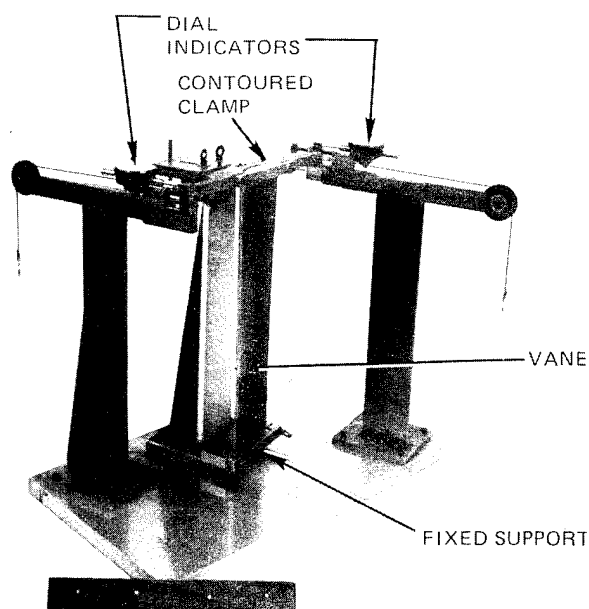


Figure 5-3 Vane Torsion Spring Rate Fixture for Application of Torque Load to Vane

5.1.3 Moisture Inoculation

After completion of static mechanical testing but prior to fatigue testing, two vanes from each of the four groups of varying material/configuration were exposed to a 60°C (140°F)/95 percent relative humidity environment for four and three weeks, respectively, for graphite and fiberglass shell parts. This accelerated moisture inoculation conditioning was required to duplicate the equilibrium moisture level expected in the trailing edge section of the vane after service operation of vanes for nine months as established by the analysis discussed in Section 3. These accelerated moisture exposure conditions were determined by exposing two-inch wide sections of scrap graphite parts to 60°C/95 percent relative humidity and measuring total weight gain as a function of time of both uncoated and polyurethane coated graphite vanes (Figure 5-4). Each data point is the average weight change of two vane section specimens. Analytical determination of weight gain resulting from the same moisture exposure conditions for a similar graphite/epoxy system (AS/3501-6) using the Springer, Reference 1, Bohlman, Reference 5 moisture diffusion approach provided excellent agreement with experimental data. As described earlier, the moisture content of the highly strained trailing edge was considered the most critical for evaluation. Therefore, the lower curve which represents weight gain in the total vane, with sections up to 6.35 mm (0.25 inch) thick, was adjusted analytically for the thinner 2.03 mm (0.08 inch) trailing edge section. As a result of this adjustment, the trailing edge section of the graphite vane can be expected to gain the required 0.8 weight percent moisture in approximately four weeks of accelerated moisture exposure.

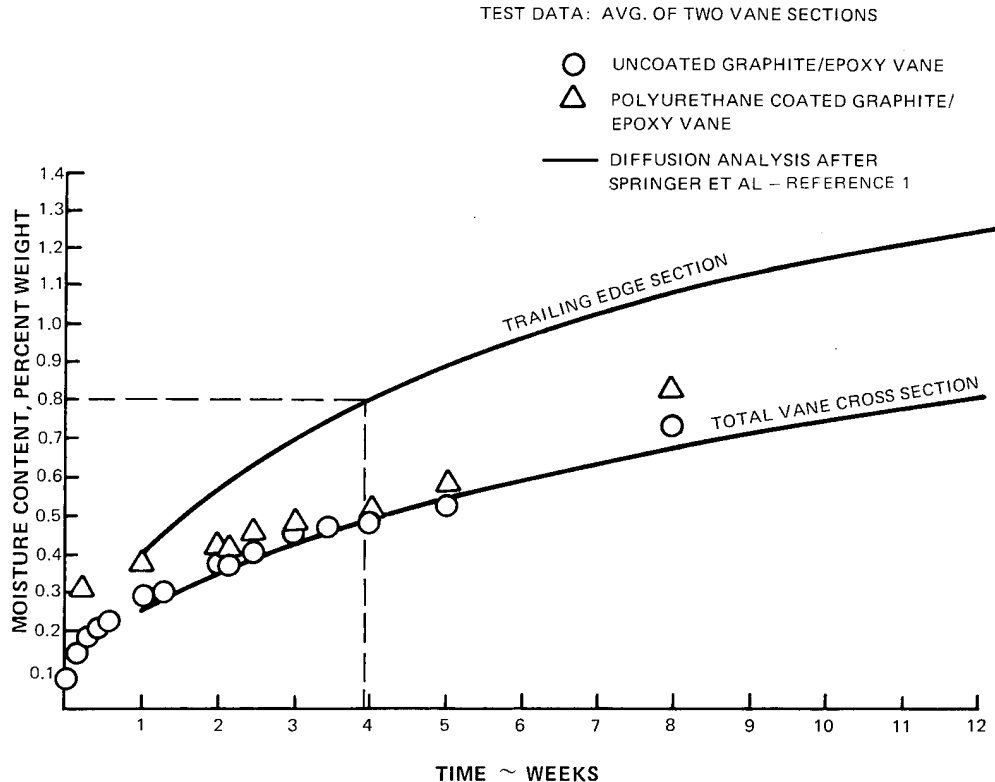


Figure 5-4 Fortafil 5A Graphite/Epoxy Shell and Core Fan Exit Guide Vane.

Similarly, the 0.9 weight percent moisture gain for the trailing edge of the fiberglass shelled vane can be achieved in approximately two and one half to three weeks of accelerated conditioning (Figure 5-5). As can be seen from moisture weight gain achieved in material specimens tested and reported in Section 4, the accelerated exposure for specimens provided reasonably good agreement with analytical data.

5.1.4 High Cycle Fatigue Tests

Vanes were prepared for fatigue testing by mounting each vane at both ends into aluminum fixtures using a 177°C (350°F) cure silicon rubber potting compound (Figure 5-6). Care was taken to prepare both the vane material and the aluminum fixture for bonding using clean and primed surfaces for maximum interface strength.

Strain gage instrumentation was installed by removing a 6.4 x 6.4 mm (0.250 x 0.250 in.) square of polyurethane coating from the vane at each planned gage location to allow installation of strain gages directly on outer shell fibers. Vanes which were fatigue tested in the warm and wet condition were instrumented with six thermocouples. A square of polyurethane was removed to allow bonding of the thermocouple junction directly to vane shell fibers.

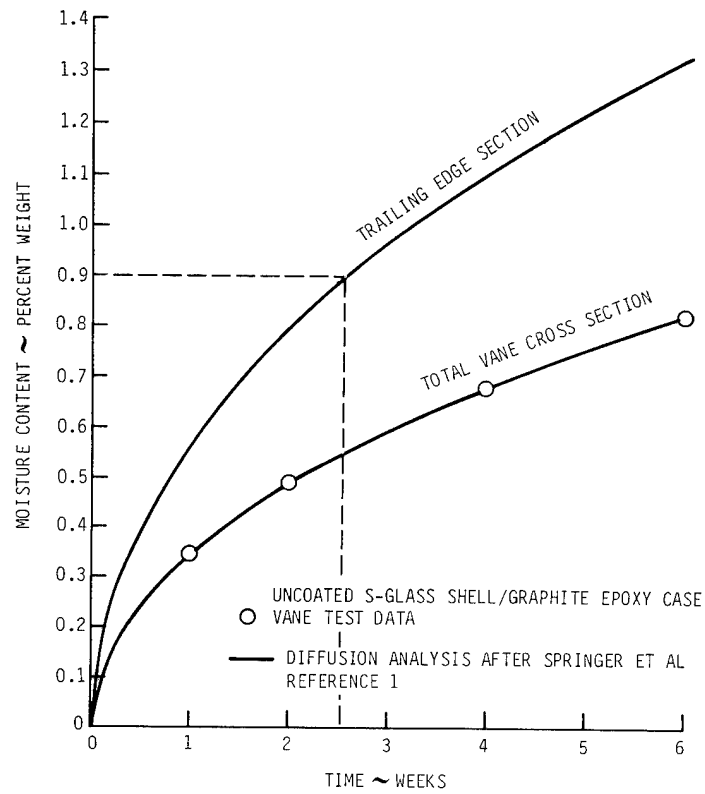


Figure 5-5 S-Glass Shell (7781/5143)/Graphite Epoxy Core Fan Exit Guide Vane

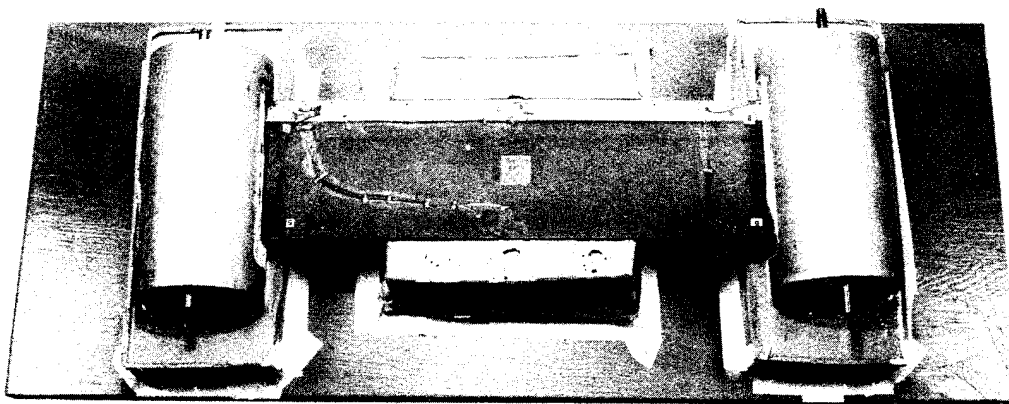


Figure 5-6 Strain Gaged Fan Exit Guide Vane Being Fixtured With End Supports in Preparation for Fatigue Testing

Prior to the application of vibratory loading, the aluminum end fixtures on the vane were turned to provide an airfoil static bending load which simulated the magnitude of aerodynamic loads experienced in the engine. Static loads were increased until the preselected trailing edge radial static strain of $-1750\mu\epsilon$ was reached. Vane corner gages were checked to confirm uniform loading of the vane; adjustments were performed as necessary. The vane end fixtures were then locked in position for the duration of the test to maintain the static load. Vanes which were tested at 60°C (140°F) in the "wet" condition, were first heated to temperature before the static load was applied to the vane. A low power resistance heater provided convective heating (Figure 5-7). No provisions were made to control moisture content during fatigue testing. However, provisions were made to maintain these vanes in a 95 percent relative humidity environment to prevent loss of moisture whenever the vibration test was being recalibrated between increasing stress levels. This was accomplished by wrapping a wet towel over the vane at room temperature.



Figure 5-7 Fan Exit Guide Vane Fatigue Test Fixture and Heater Assembly

After static loads were stabilized, vibrational loading in the first bending mode was introduced (See Figure 3-12 for frequency ranges). When the test vane successfully completed 10^7 cycles at any one vibrational strain level, strain was progressively increased until a frequency loss indicated failure. The sequence for increasing strain increments on test vanes is presented in Figure 5-8. Strain at failure was considered quite conservative, since many vanes were tested at 10^7 cycles for up to six times before failure occurred. An Unholtz Dickie 42.4 KN (9500 lbs.) electrodynamic exciter was used to vibrate the part (Figure 5-9). The exciter frequency was varied until vane first bending resonant frequency was achieved. Exciter amplifier gain was adjusted to establish the required vane TE dynamic strain level. A telemicroscope was focused on the vane TE at midspan and the relationship between vane TE dynamic strain and vibratory amplitude was determined. The short life of strain gage instrumentation during dynamic testing forced reliance on the telemicroscope method for monitoring trailing edge strain.

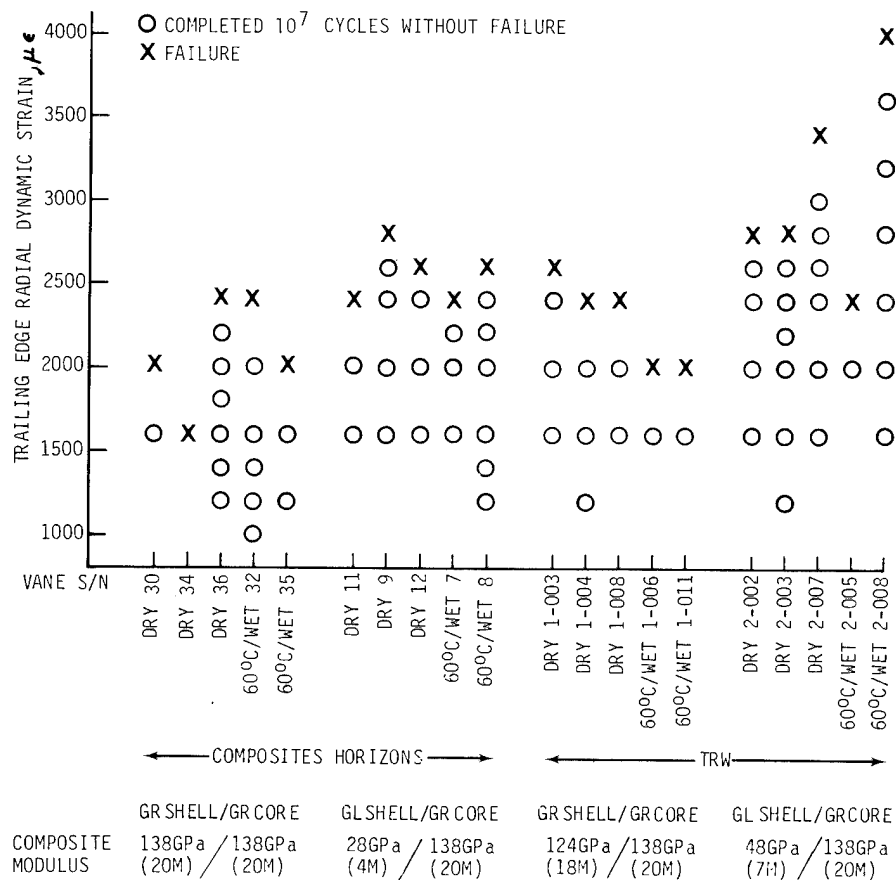


Figure 5-8 Summary of Fatigue Test Program Dynamic Loading Sequence - Composite Fan Exit Guide Vanes

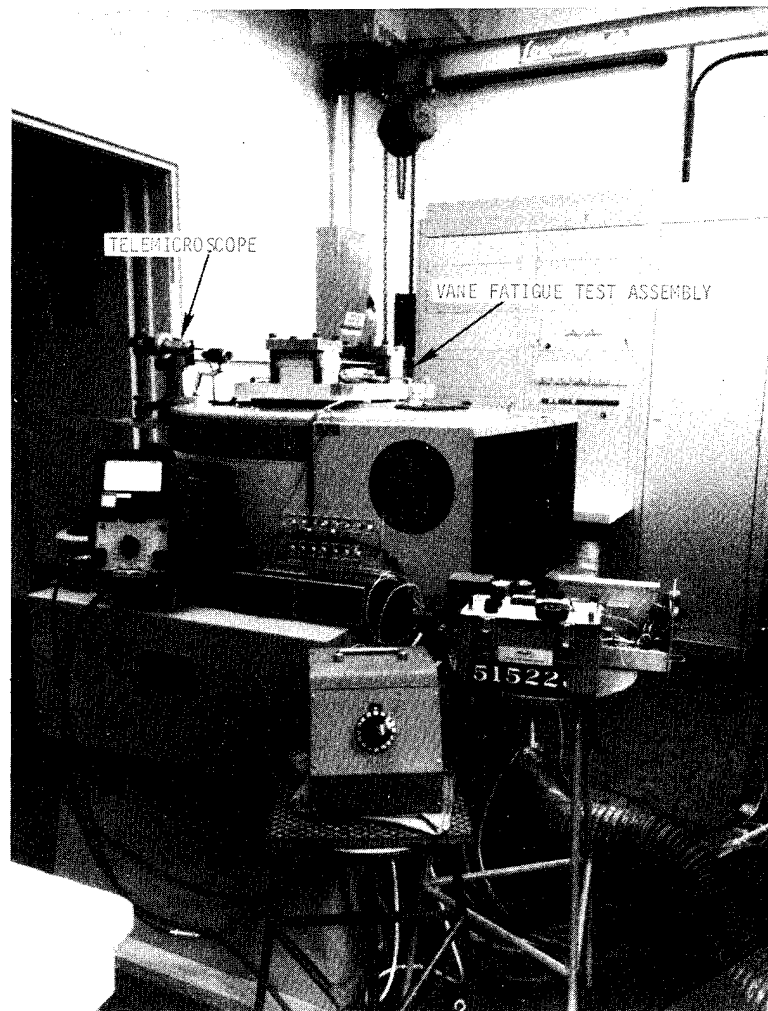


Figure 5-9 Unholtz-Dickie 42.4 KN (9500 lb) Electrodynamic Exciter

5.2 FATIGUE TEST RESULTS

5.2.1 Summary

The fatigue test program provided comparative vane durability results. Evaluation of dynamic strain data at 10^7 cycles to fatigue failure showed that the glass shell/high modulus graphite core vanes failed at higher strain levels than graphite shell/high modulus graphite core vanes; $2000\mu\epsilon$ vs $1600\mu\epsilon$, respectively (Figure 5-10). All the vanes within each of these two material groups appeared to have a similar minimum fatigue strength. This minimum occurred although material,

configuration and process changes existed. For example, graphite and fiberglass shell material were of varying fiber moduli. The number of continuous shell plies at the trailing edge varied between vendors and were further influenced by molding techniques which resulted in some expulsion of graphite fiber at the trailing edge. One vendors' product contained kinked fiber near the trailing edge and vane porosity. In addition vanes varied in bending and torsional stiffness for each group and were fatigue tested at various levels of moisture content. The insensitivity of the vane to these material, process and environment effects is testimony to the adequacy of vane design and improvements in materials since the early 1970's.

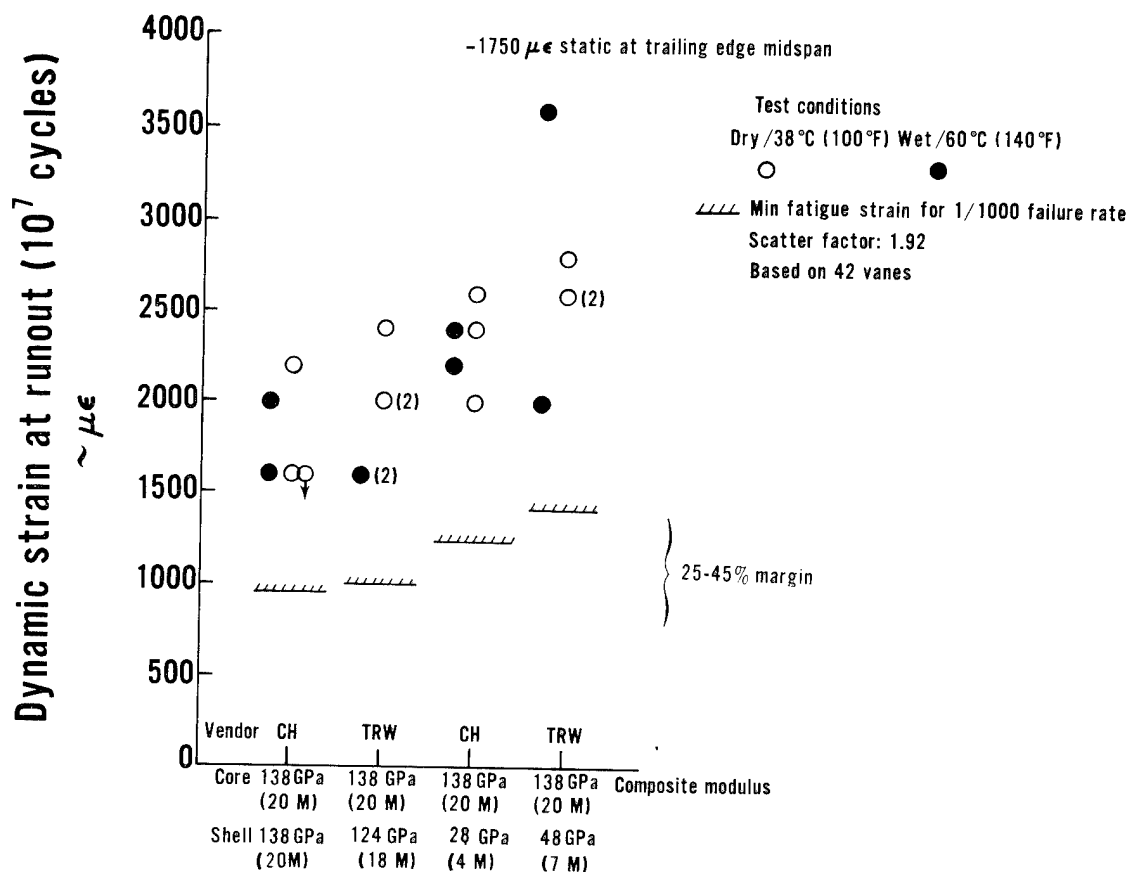


Figure 5-10 Composite Fan Exit Guide Vane Fatigue Strain Capability

5.2.2 Minimum Fatigue Strain Capability

Fatigue data for 20 vanes in this program was Weibull treated to establish a minimum fatigue strain capability for each of the four material/

design configuration vanes. Minimum fatigue strain capability was defined as a one in one thousand vane failure rate.

Data treatment to obtain minimum fatigue strain requirements are illustrated below.

1. Mean strain was established for each of four configurations by averaging five data points from each configuration. For example, for 124 GPa (18 M) modulus shell fiber, the mean strain is determined as shown below.

<u>ϵ Runout ($\mu\epsilon$)</u>	<u>Runout/ Mean (ϵ / ϵ mean)</u>
2400	1.250
2000	1.042
2000	1.042
1600	0.833
1600	0.833
<u>Mean</u>	
1920 $\mu\epsilon$	

2. The population of vanes fatigue tested to endurance limit was Weibull plotted (Figure 5-11) as percent failed vs. ϵ / ϵ mean to establish a "scatter factor". From the data we obtain:

$$\text{Scatter Factor} = \frac{\epsilon / \epsilon \text{ mean at } 50\%}{\epsilon / \epsilon \text{ mean at } 0.1\%*} = \frac{1.0}{0.45} = 2.2$$

*(one failure in one thousand)

3. To provide additional confidence in estimating minimum fatigue strength, an additional 22 data points, some of which reflect 1975 vintage poor quality production parts, were added to the Weibull distribution. This resulted in a 42 point data Scatter Factor change to 1.92 (Figure 5-12). The minimum fatigue strain capability for the increased sample size was:

$$\text{Minimum Fatigue Strain} = \frac{1920 \mu\epsilon}{1.92} = 1000 \mu\epsilon$$

The minimum fatigue strain Weibull computed values for a failure rate of 1 in 1000 parts of the four vane designs is shown in Figure 5-10. The minimum fatigue strain for all four configurations varied from less than 1000 $\mu\epsilon$ to slightly less than 1500 $\mu\epsilon$ which, in all cases, was significantly below the vibratory fatigue strain failure for any part during fatigue testing. Static and dynamic fan exit guide vane strain was determined in the earlier thin trailing edge

program in an engine environment. Strain adjustments were made for each vane design/material tested for the new thicker trailing edge part operating in a typical JT9D engine. The difference between the minimum fatigue strain and the anticipated engine dynamic strain for the thick trailing edge vane provided a factor of 25-45 percent fatigue margin. The lower modulus glass shelled vanes exhibited the largest margin whereas the higher modulus graphite shell vanes displayed a somewhat reduced margin.

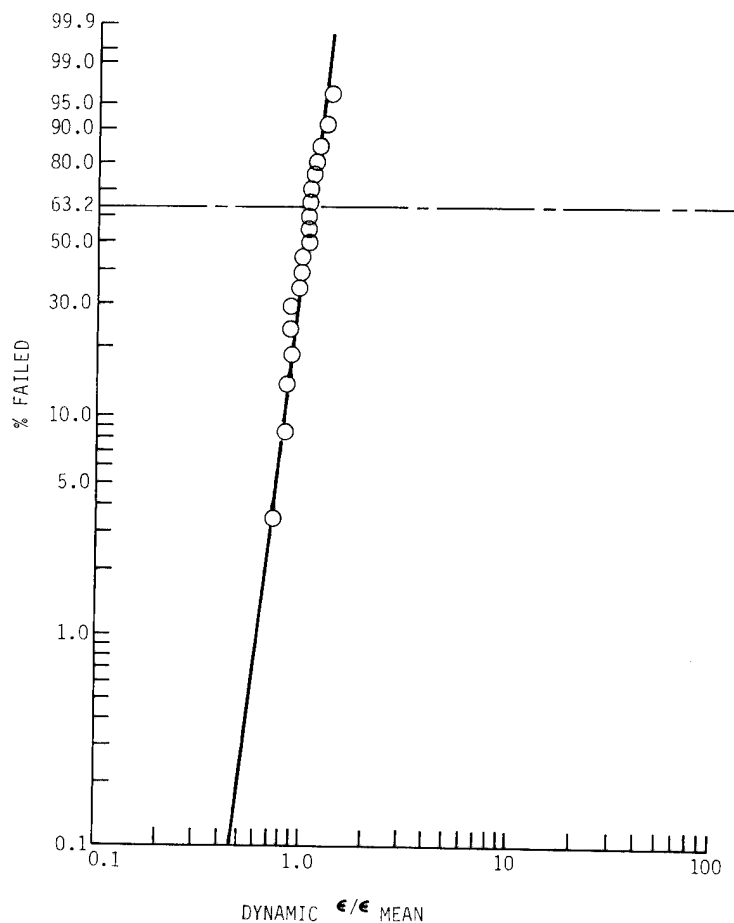


Figure 5-11 Weibull Plot Composite FEGV Fatigue Test Data-NASA Program

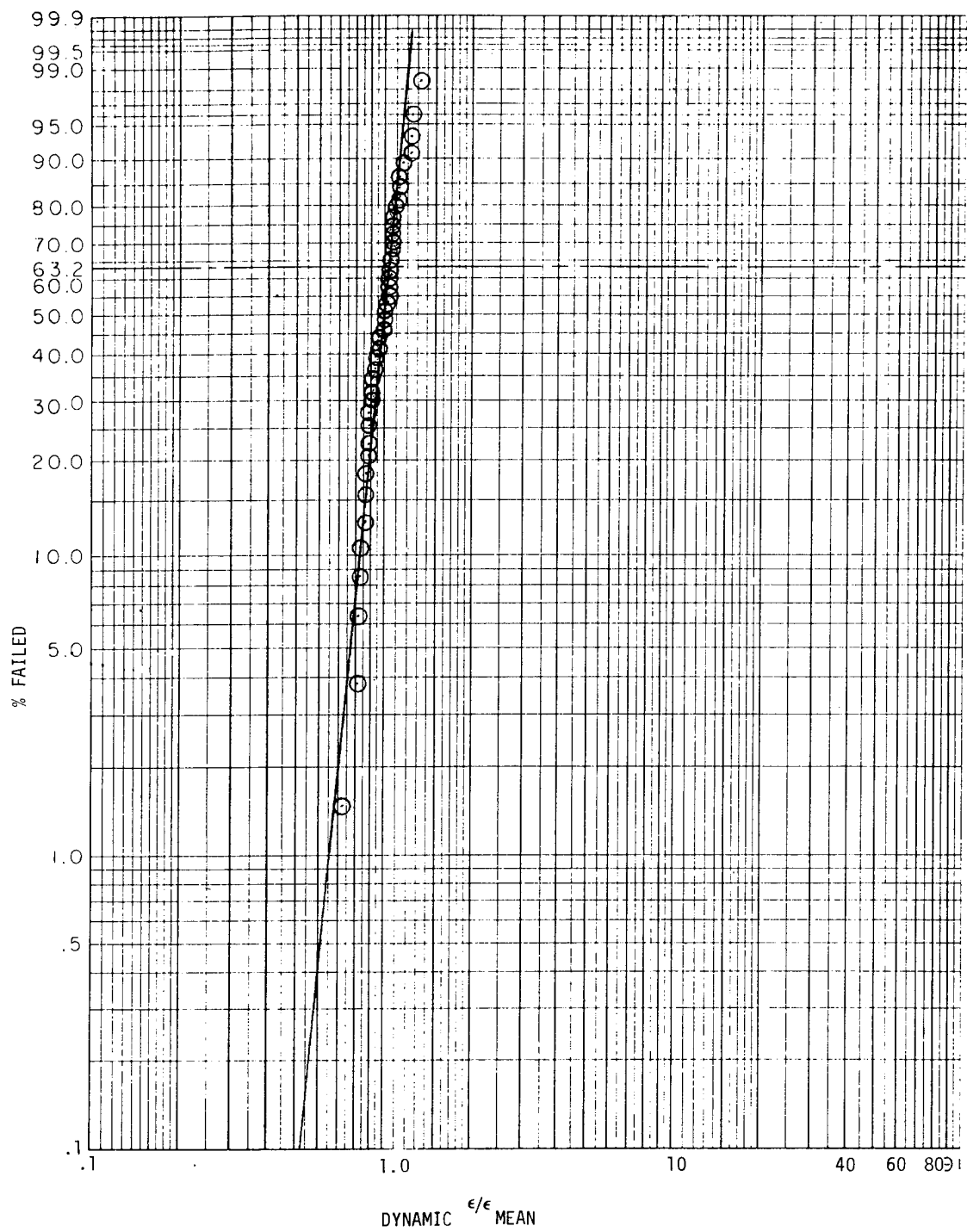


Figure 5-12 Weibull Plot Composite FEGV Fatigue Test Data - All Data

5.2.3 Failure Mode

Several different failure modes were noted for the four material configurations. The patterns and locations for failures were essentially consistent within any one material configuration. Shell fiber modulus was most important in determining the torsional and uncamber stiffness of the airfoil and a relationship is apparent between failure location, mode and torsional stiffness. Differences in torsional stiffness between two all graphite configurations ranged from 2.38 M-N/deg (21 in. lb/deg.) to 1.77 M-N/deg. (16 in. lb/deg.). Failure location and mode were essentially identical for all of these ten vanes fabricated with graphite regardless of shell modulus material. Vanes failed under vibratory load at approximately the midspan location at the trailing edge (Figures 5-13, 5-14 and 5-15). A combination of different types of cracking was common to these vanes. Visually, shell cracking parallel and transverse to fibers was observed. In addition shell separation from the core section was apparent. Radiographic examination confirmed two additional types of cracking, transverse and longitudinal core cracks. These will be shown in Section 5.2.4. It can be speculated from microexamination performed after testing and reported in Section 5.2.6 that shell-to-core shear failure occurred first, followed by shell cracking, transverse cracking of core, and longitudinal core cracking. It is also possible, especially for the lower torsional stiffness graphite shell fiber vanes (124 GPa), that longitudinal core cracking may have occurred first, followed by shell deterioration.

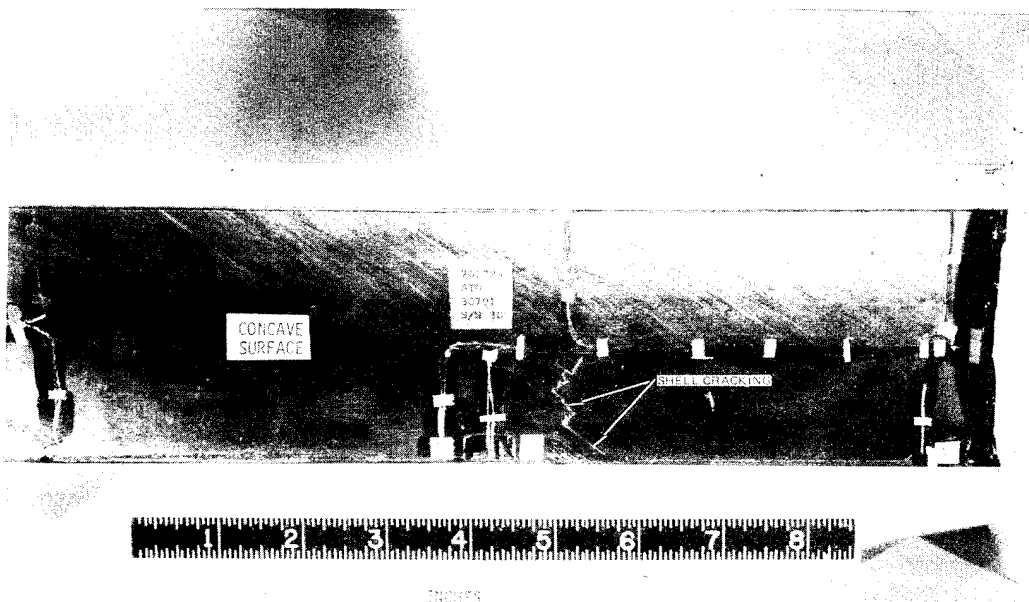


Figure 5-13 Photograph of Fatigue Tested Composites Horizons
Graphite/Epoxy Vane

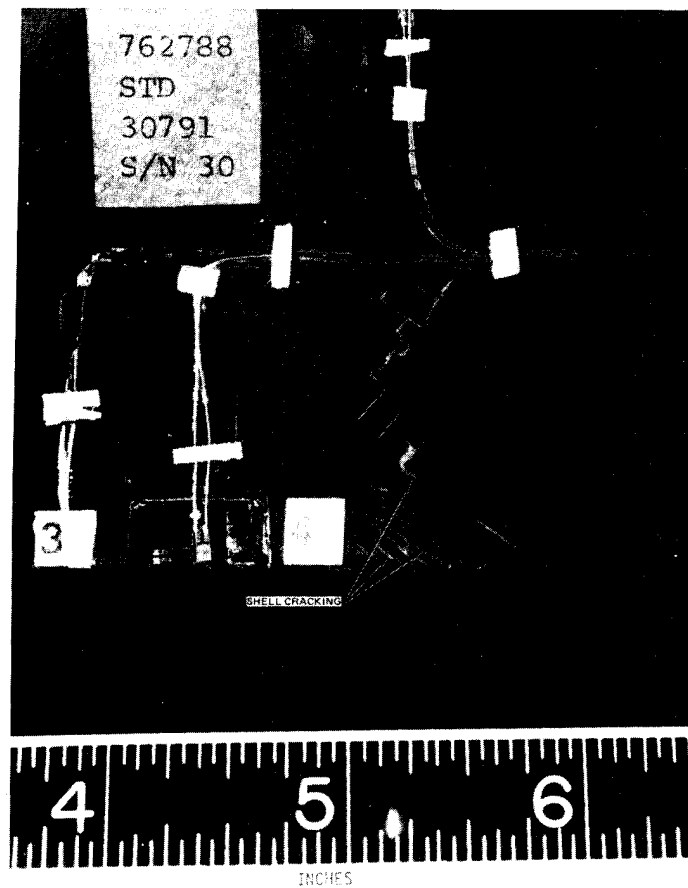


Figure 5-14 Photograph of Fatigue Tested Composite Horizons Graphite/Epoxy Vane

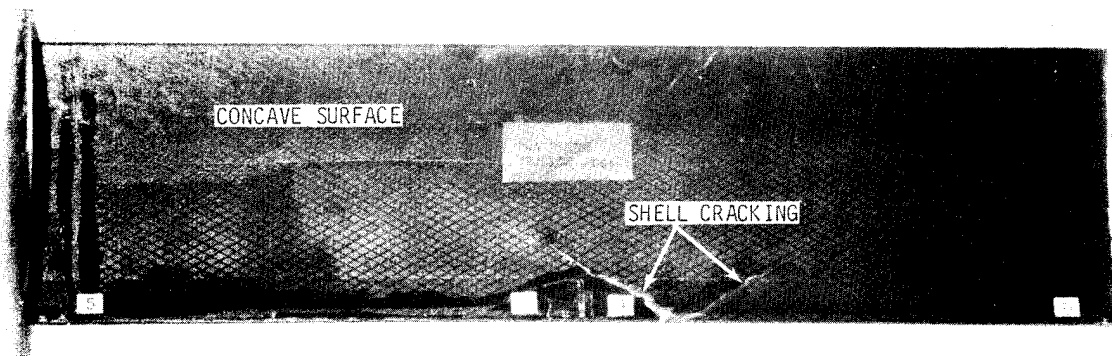


Figure 5-15 Photograph of Fatigue Tested TWG Graphite/Epoxy Vane

The two fiberglass shell lower torsional stiffness configurations, fabricated by different vendors, showed different failure modes. The higher torsional stiffness vanes in this group fabricated with unidirectional fiberglass shell plies failed transverse to the span at the vane attachment (Figure 5-16). It was interesting to note that one vane in this unidirectional fiberglass shell group (Figure 5-17) which exhibited the lowest torsional stiffness of that group 1.24 M-N/deg (11 in. lb/deg.), failed in a combined mode of the higher torsional stiffness vanes (transverse core cracks at trailing edge) and the lowest torsional stiffness vanes (radial cracking away from the trailing edge). The lowest torsional stiffness vanes failed by radial cracking of the core approximately 2.5-3.0 cm (1.0-1.2 in.) from and parallel to the trailing edge. The crack was visible as a "stress whitened" line on the convex side and a crack on the concave side (Figure 5-18). No trailing edge cracking transverse to the airfoil occurred. It is apparent that the group of lowest torsional stiffness vanes were being excessively uncambered at the trailing edge during fatigue testing. A summary of vane stiffness parameters and failure modes for the four vane configurations is presented in Figure 5-19.

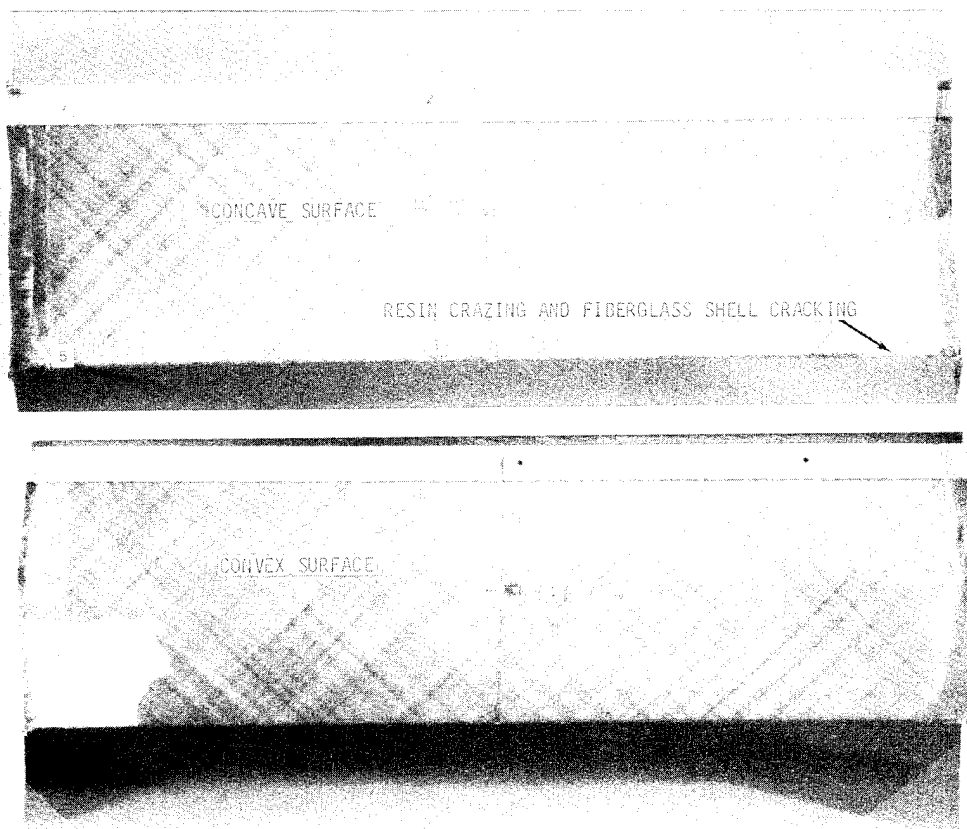


Figure 5-16 Photograph of Fatigue Tested TW Glass Shell - Graphite Core/Epoxy Vane

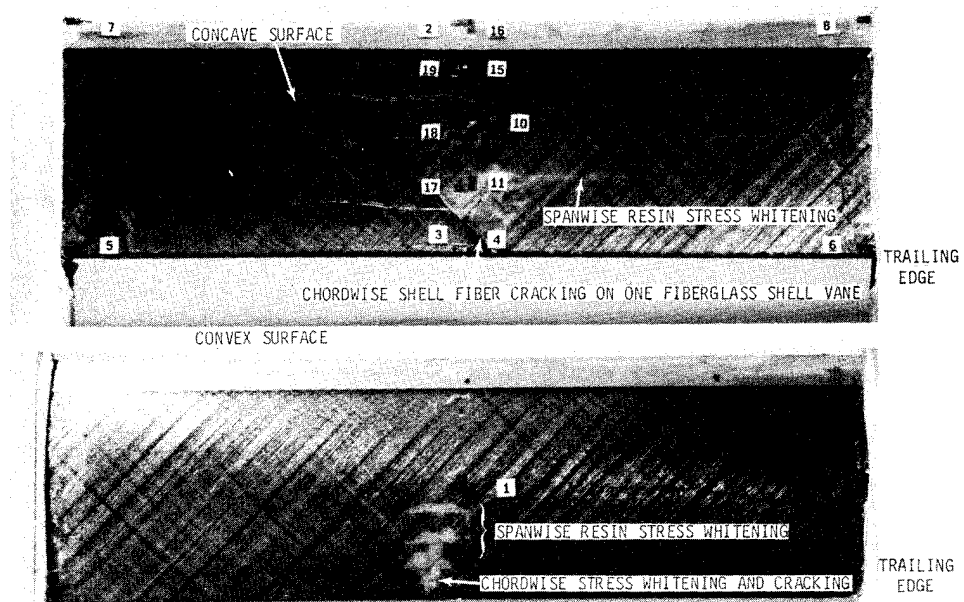


Figure 5-17 Photograph of Fatigue Tested TRW Glass Shell - Graphite Core/Epoxy Vane

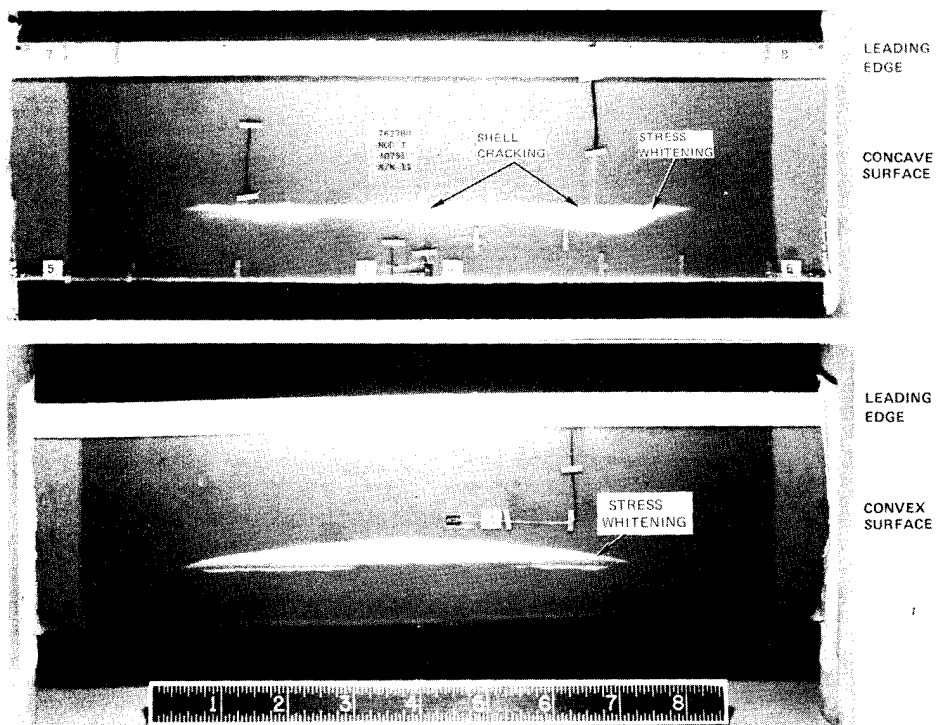


Figure 5-18 Photograph of Fatigue Tested Composites Horizons Hybrid Glass Shell - Graphite Core/Epoxy Vane

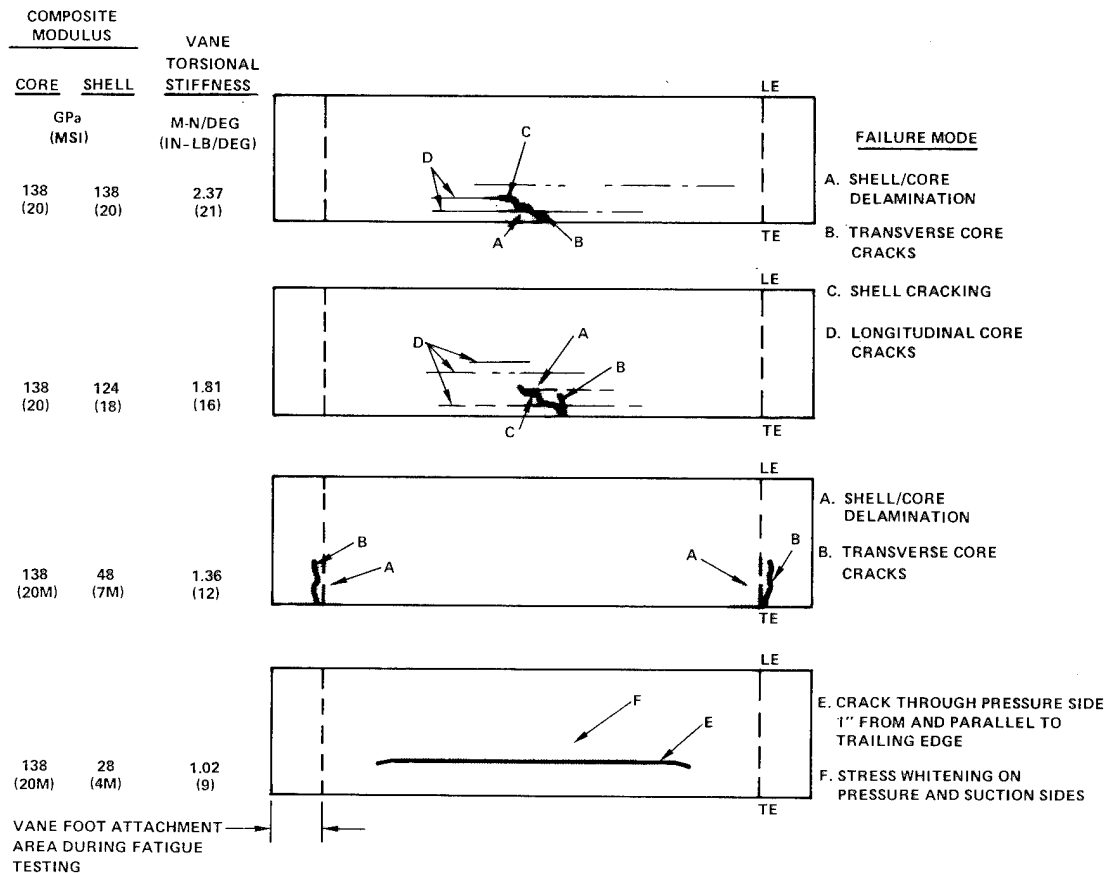


Figure 5-19 Composite Fan Exit Guide Vane Failure Mode Summary

5.2.4 Post-Test Nondestructive Analyses

At the termination of fatigue testing of each vane, failure was apparent as a result of frequency shift and visual appearance. In all cases, visible failure of the composite airfoil was evident. Radiographic analysis was performed for each vane after failure to determine failure areas not apparent during visual examination.

Evaluation of all graphite vanes showed similar radiographically documented failure modes (Figures 5-20 and 5-21). Transverse core and shell cracking was observed at the midspan trailing edge at the point of maximum strain. Longitudinal cracking through the core was also observed decreasing in intensity with distance from the trailing edge. No other flaws or material/structural abnormalities were detected.

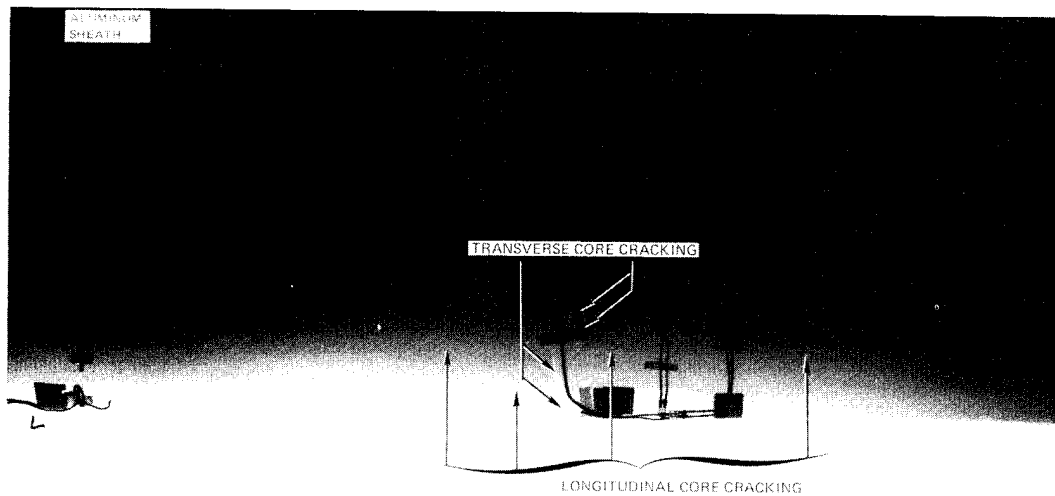


Figure 5-20 *Print from Radiograph of Composites Horizons Graphite/Epoxy Vane After Fatigue Test (Vane No. 30)*

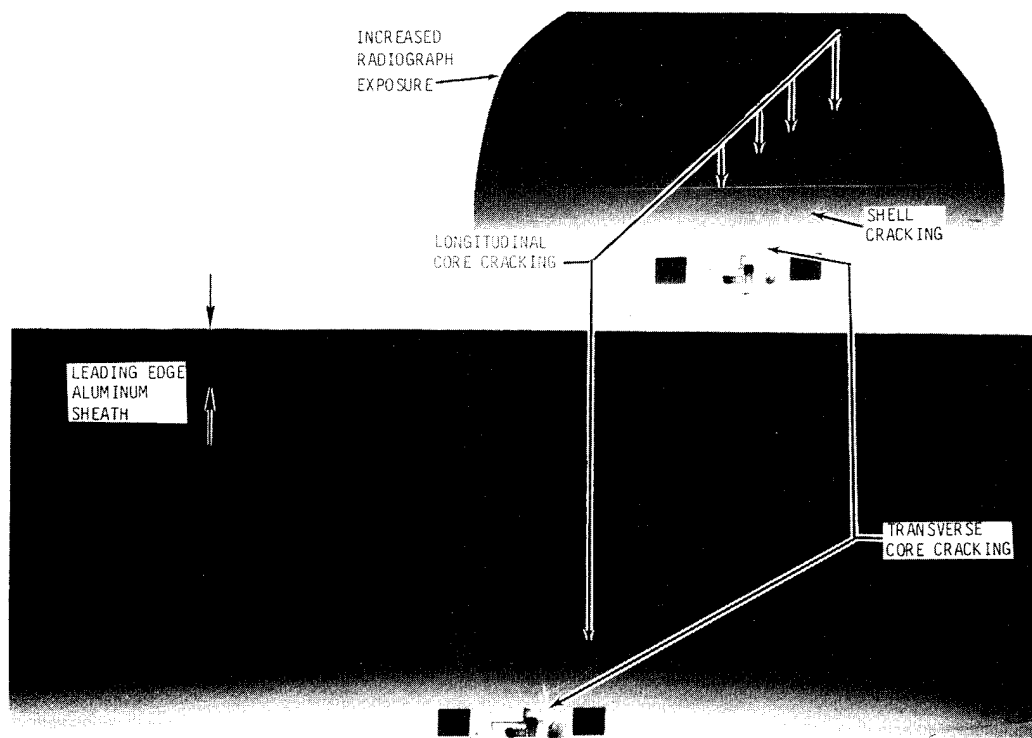


Figure 5-21 *Print from Radiograph of TRW Graphite/Epoxy Vane After Fatigue Test (Vane No. 1-011)*

Examination of the two fiberglass shell/graphite core vanes of two different material/designs revealed different cracking patterns and some differences in quality. The Composites Horizons' vane which was fabricated using fiberglass cloth and represented the lowest modulus shell, presented a more uniform density image to radiography (Figure 5-22). Examination of radiographic films indicated the failure mode followed the visually observed pattern and ran spanwise through both the core and shell approximately 25 mm (1 inch) in from the trailing edge; no other deviations were noted. Examination of the TRW fiberglass ply fabricated shell revealed a cracking pattern at the trailing edge which was adjacent to the vane attachment. Variations in shell fiber density and some fiber wrinkling were also evident (Figures 5-23 and 5-24).

5.2.5 Failure Stress Analyses

Variations in failure mode were detected sufficiently early in the program to permit supplementary strain gaging for strain profiling of all four configurations. At least one vane of each configuration was strain gaged to monitor both chordwise and radial strain at both static and dynamic conditions. All configurations showed similar chordwise distributions of static and dynamic radial strain with a maximum compressive strain at the trailing edge (Figure 5-25). However, dynamic chordwise strains in the chordwise direction (Figure 5-26) indicated peak strain 2.5 cm from the trailing edge which corresponded to the failure location for the fiberglass cloth shell part which was the lowest torsional stiffness vane configuration. Apparently, three of the four configurations had sufficient torsional strength to avoid a spanwise primary failure in the form of uncambering parallel to the trailing edge; the lowest torsional stiffness vane category with a fiberglass cloth shell failed by uncambering.

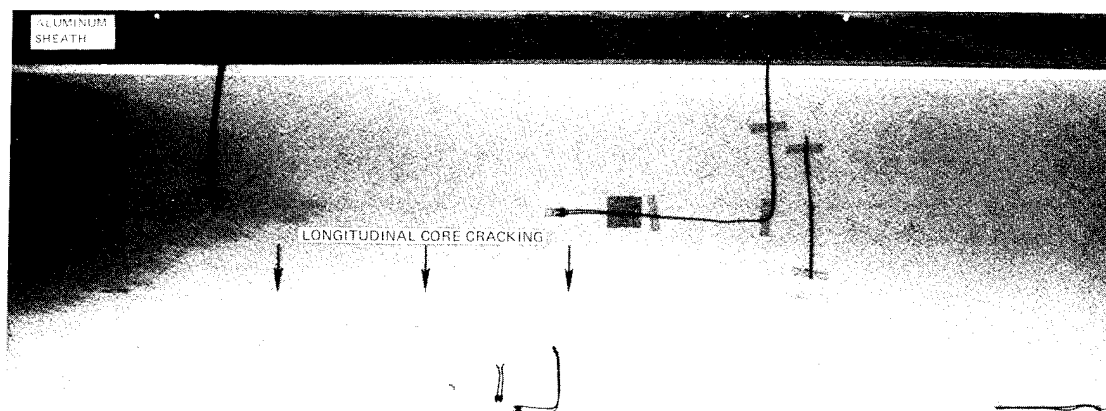


Figure 5-22 *Print from Radiograph of Composites Horizons Fiberglass Cloth Shell-Graphite Core/Epoxy Vane After Fatigue Test (Vane No. 9)*

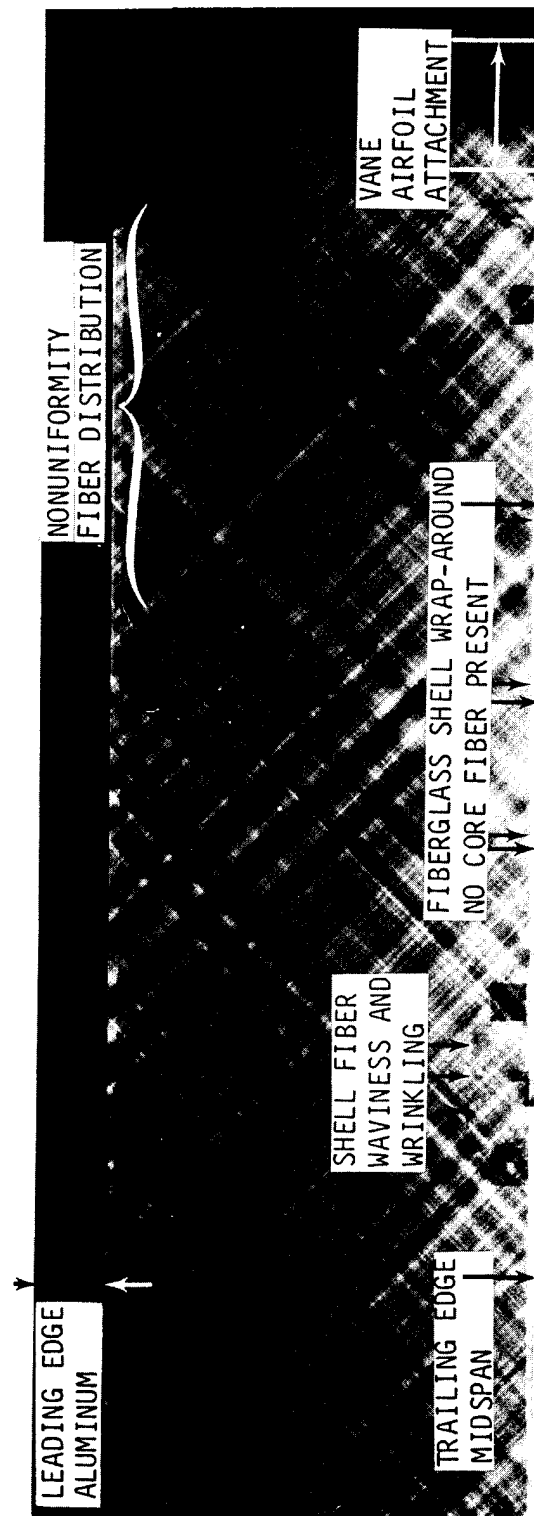


Figure 5-23 Print from Radiograph of TRW Fiberglass Shell-Graphite Core/Epoxy Vane After Fatigue Test (Vane No. 2-008)

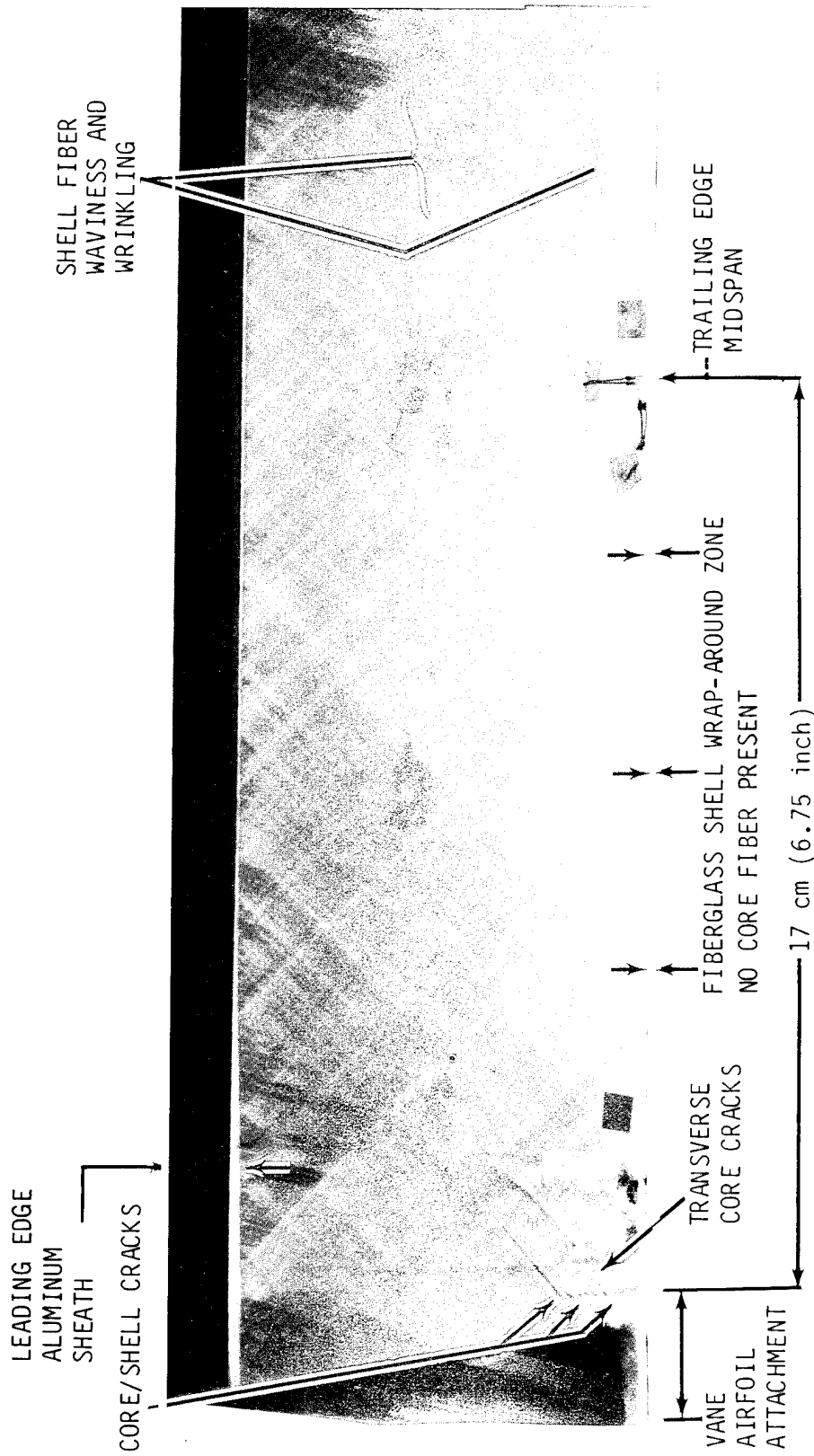


Figure 5-24 Print from Radiograph of TW Fiberglass Shell-Graphite
Core/Epoxy Vane After Fatigue Test (Vane No. 2-005)

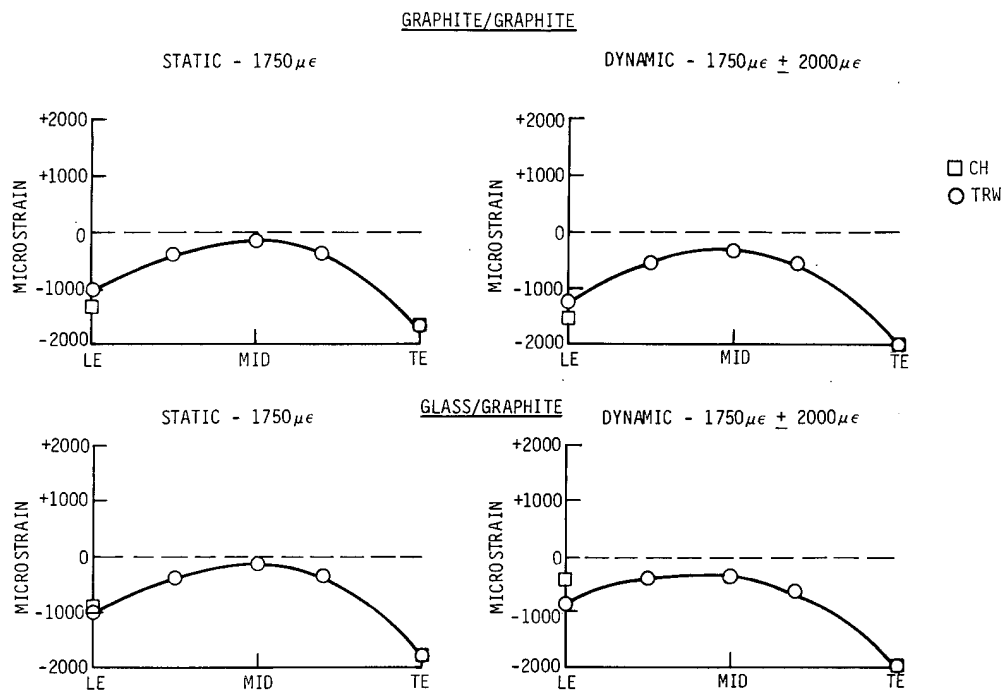


Figure 5-25 Chordwise Distribution of Radial Strain on Concave Surface for Graphite and Hybrid Vanes

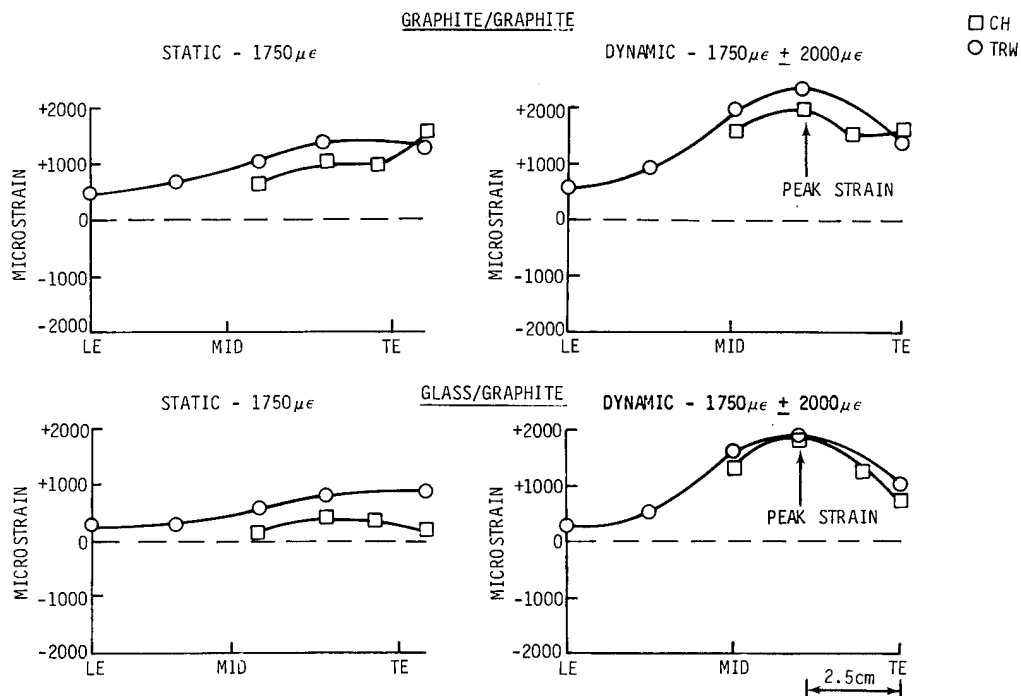


Figure 5-26 Chordwise Distribution of Chordwise Strain on Concave Surface for Graphite and Hybrid Vanes

5.2.6 Post-Test Microstructure Analysis

Chordwise sections for microstructure analyses of typical failed vanes were taken to document failure initiation and progression. Highest torsional stiffness vanes fabricated with graphite shell material failed at the vane midspan trailing edge (Figures 5-27, 5-28 and 5-29). After examination of sections from these vanes, it was postulated that delamination initiated in interlaminar shear at the interface between the core and shell plies at the trailing edge. This resulted in local decoupling of the shell from the core and reduced local torsional stiffness which increased the local uncamber of the airfoil. This, in turn, promoted intraply cracking of the unidirectional core. As the core lost its integrity at the trailing edge, it was subjected to transverse fiber cracking which is more apparent on radiographs in Section 5.2.4. Under these conditions the loosened shell, which did not have the strength to withstand the high frequency fatigue loads, continued to crack. No significant visible differences were detectable between the failure mode of the 345 GPa and 207 GPa fiber modulus graphite shell vanes. However, one difference in cracking pattern was noted upon microstructure examination. The lower modulus graphite fiber shell vane experienced radial direction core cracking further from the trailing edge (Figure 5-29). The presence of porosity in the lower modulus vane did not appear to influence failure mode.

By contrast to high torsion stiffness graphite shell vanes, the lower torsion stiffness fiberglass vanes experienced considerably less shell damage. The primary damage was in the core and the zone between the shell and the core (Figures 5-30, 5-31 and 5-32). It is interesting to note that the vane trailing edge did not become excessively distressed. The failure patterns on the fiberglass shell vanes are visually apparent from the appearance of stress whitening, craze cracking and visible delamination of the fiberglass shell from the graphite core. Although the failure locations for the fiberglass shelled vanes varied as a function of shell stiffness, the failure mode appeared similar. It is anticipated that shell-to-core shear failure resulted in local loss of airfoil camber stiffness and that radial intraply cracking of the core followed. Failure locations were confirmed from analytical and experimental strain data.

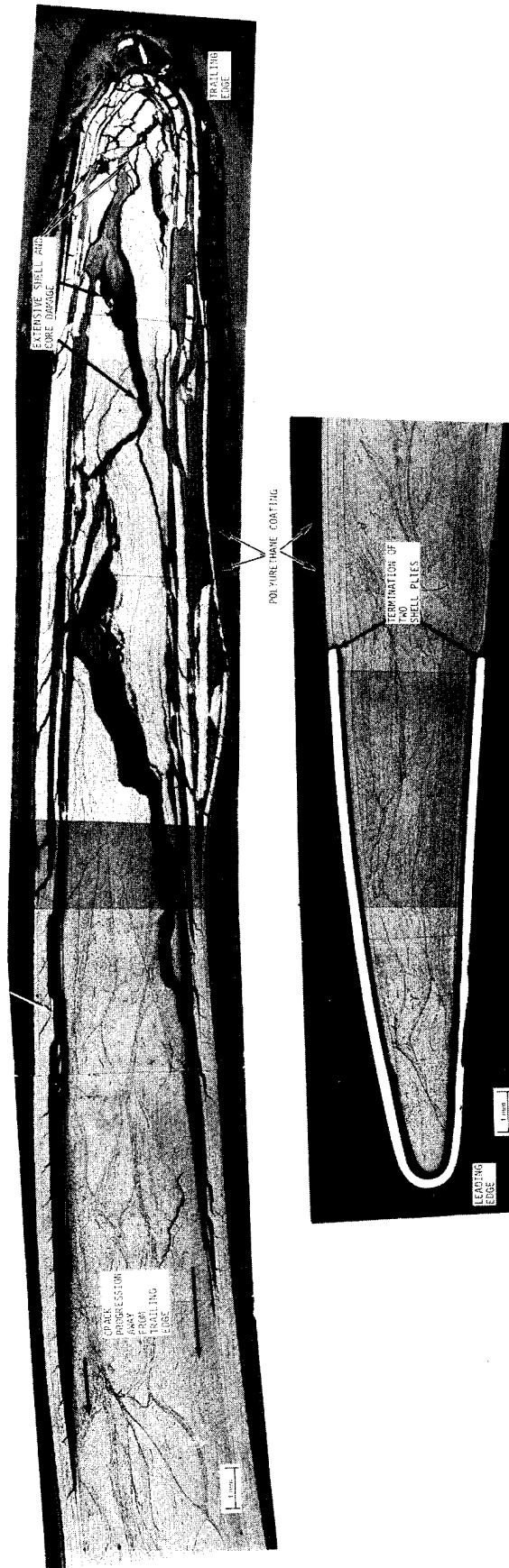


Figure 5-27 Photomicrograph of Graphite/Epoxy Fan Exit Guide Vane Fatigue Failure

- o Transverse section through vane midspan at maximum damage zone
- o Composites Horizons; 345 GPa modulus fiber shell and core; vane S/N 32

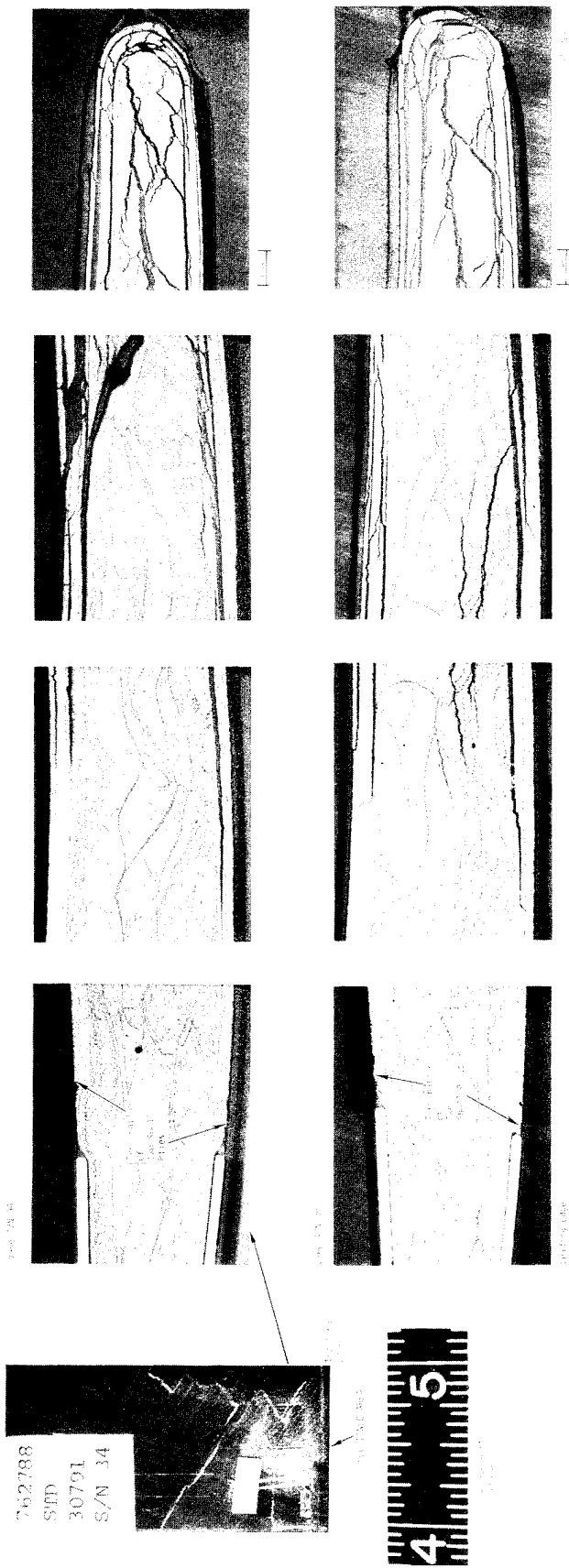


Figure 5-28 Photomicrograph of Graphite/Epoxy Fan Exit Guide Vane Fatigue Failure

- o Transverse sections through vane midspan displaced 6mm from maximum damage zone
- o Composites Horizons; 345 GPa modulus fiber shell and core; vane S/N 34

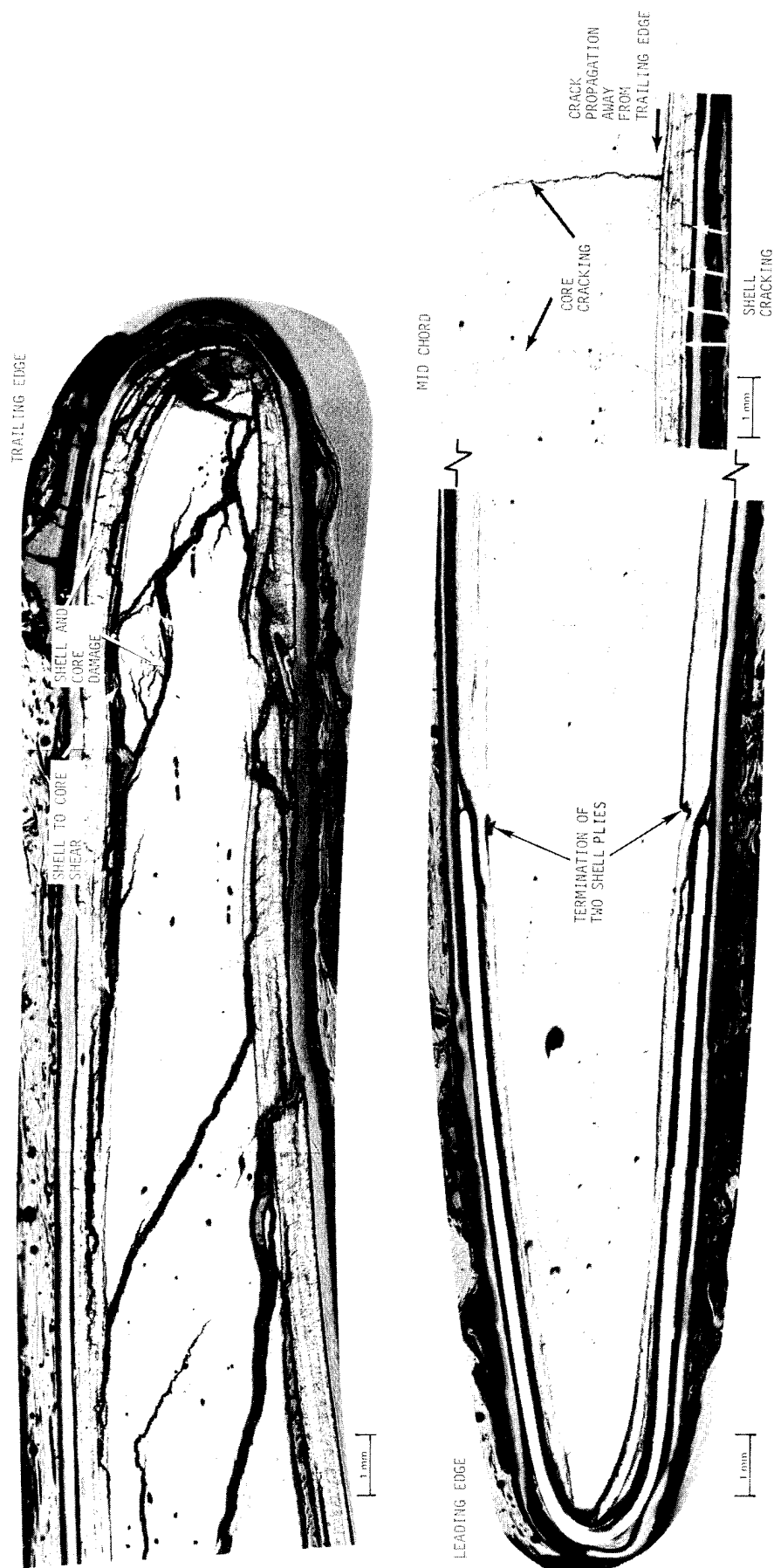


Figure 5-29 Photomicrograph of Graphite/Epoxy Fan Exit Guide Vane Fatigue Failure

- o TRW; 207 GPa modulus shell fiber; 345 GPa modulus core fiber; vane S/N 1-011

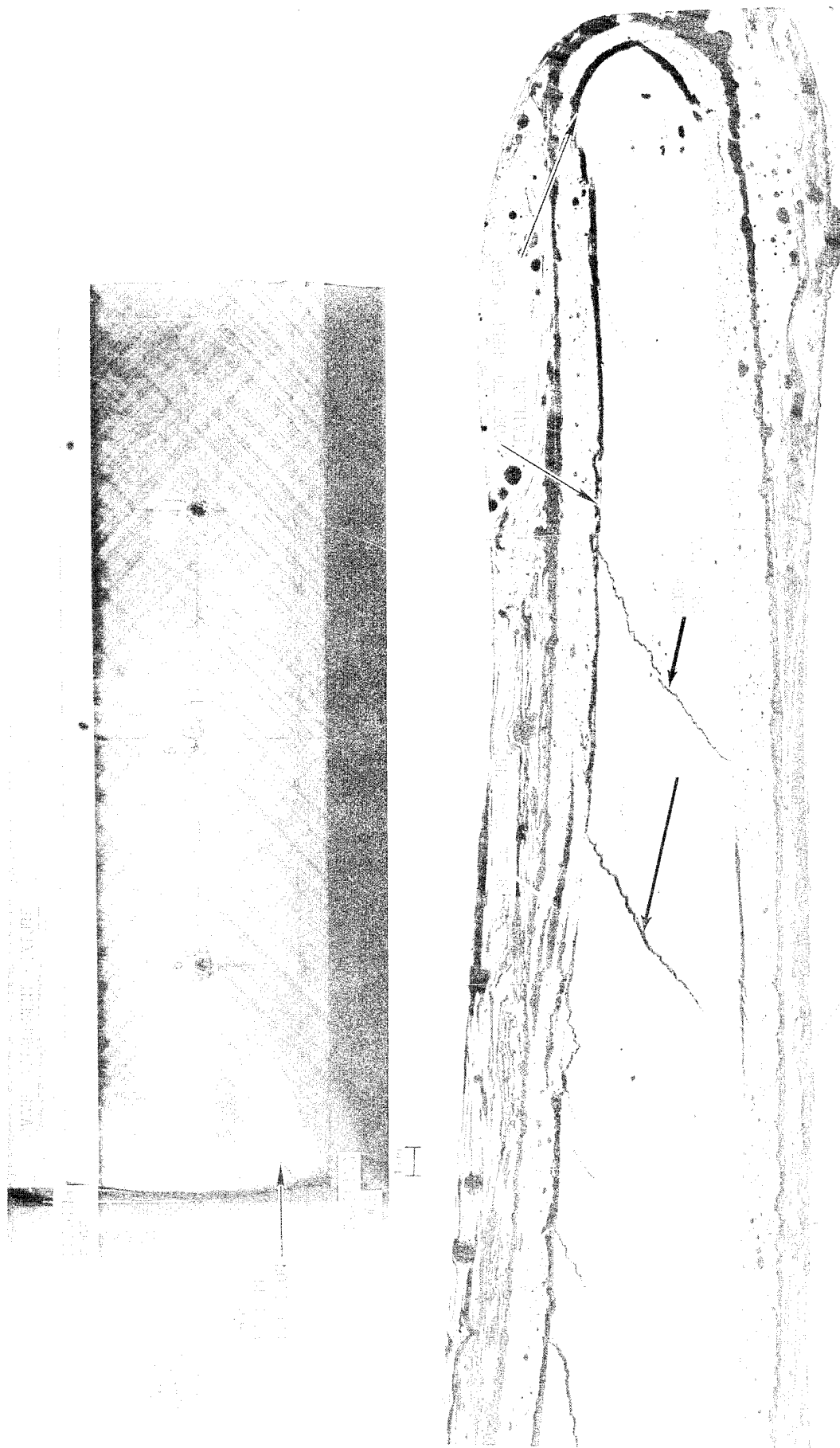


Figure 5-30

Photomicrograph of Hybrid Glass Shell-Graphite/Epoxy
Core Fan Exit Guide Vane Fatigue Failure

- o Transverse section through vane at attachment fixture
- o TW; 83 GPa modulus shell fiber; 345 GPa modulus core fiber; Vane S/N 2-005



Figure 5-31 Photomicrograph of Hybrid Glass Shell-Graphite/Epoxy Core Fan Exit Guide Vane Fatigue Failure

- o Transverse section through vane midspan
- o TRW; 83 GPa modulus shell fiber; 345 GPa modulus core fiber; Vane S/N 2-003

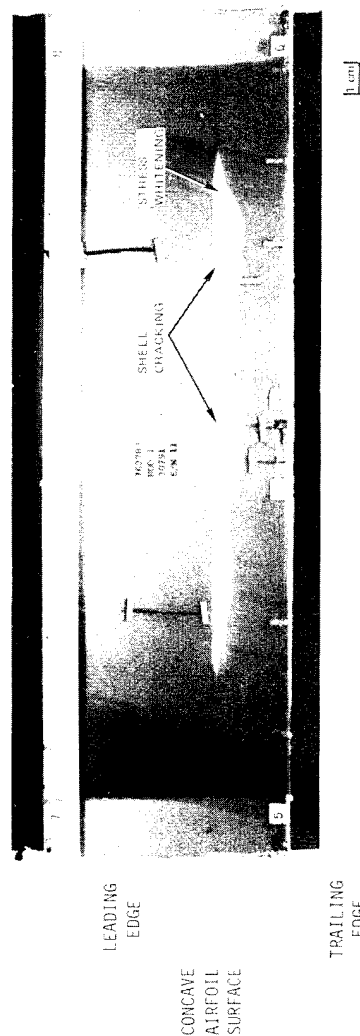
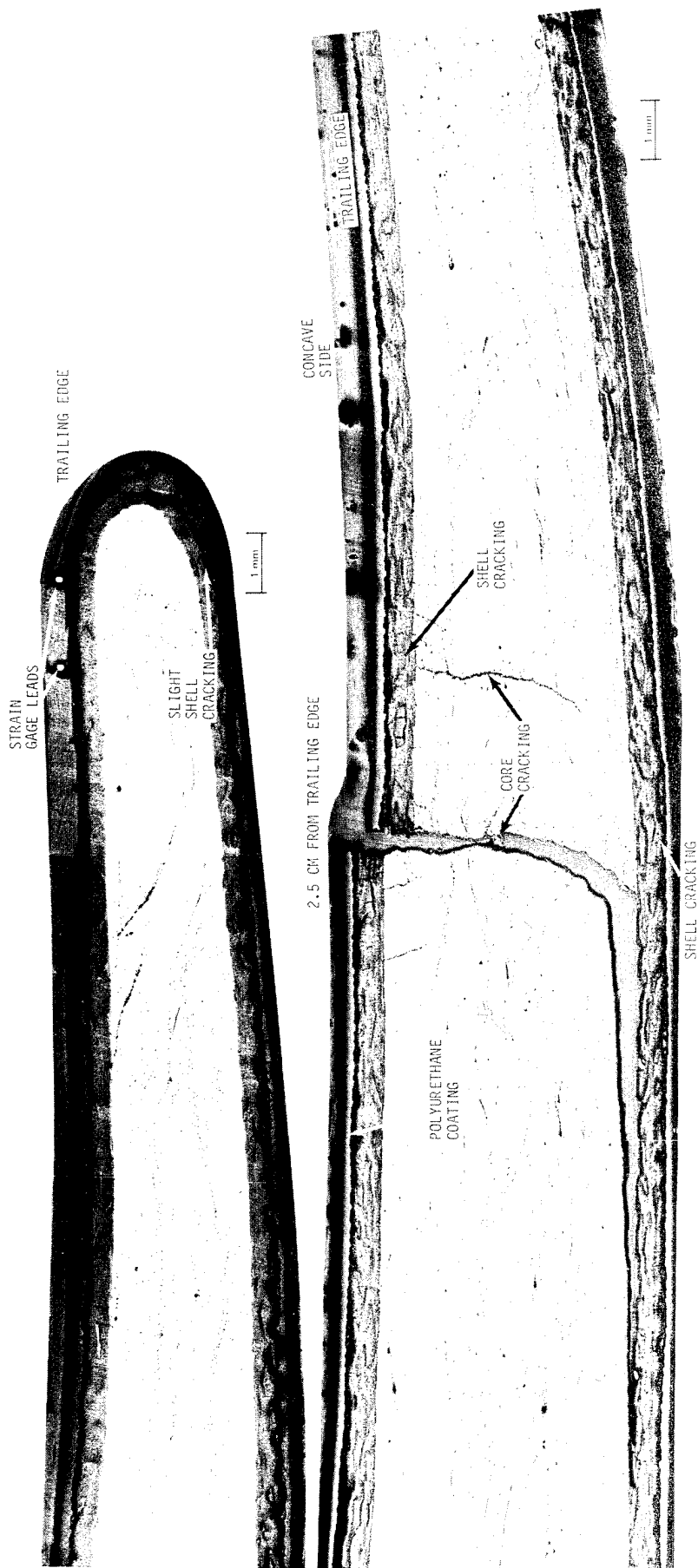


Figure 5-32 Photomicrograph of Hybrid Glass Cloth Shell-Graphite/ Epoxy Core Fan Exit Guide Vane Fatigue Failure

- o Transverse section through vane midspan
- o Composites Horizons; 41 GPa modulus shell cloth; 345 GPa modulus core fiber; Vane S/N 11

6.0 CONCLUSIONS

6.1 CONCLUSIONS

All of the objectives of the subject contract were achieved and are summarized in the conclusions presented below:

- o All four thick trailing edge composite fan exit guide vane configurations exhibited fatigue strain capability in excess of established requirements. Two of the material/ply orientation combinations with reduced shell ply stiffness exhibited increased fatigue margin compared to stiffer shell configurations.
- o Vanes produced by two vendors and fabricated using different processes, epoxy material and shell fiber showed similar fatigue performance behavior. The presence of some fiber wrinkling and higher levels of porosity evident in one vendor's product did not affect fatigue performance.
- o A correlation was shown to exist between vane fatigue failure mode and torsional stiffness.
- o Composite vane polyurethane coating integrity and bond interface strength were not degraded during fatigue testing under dry or wet conditions.
- o A correlation was established between static and dynamic strain gage data, NASTRAN analysis, and modes of failure for each of the material/ply orientation vane configurations tested.
- o Experimental laboratory data substantiated the computer model developed for predicting moisture weight gain in composite fan exit guide vanes expected from service operation.
- o The presence of up to 0.8 weight percent moisture in composite vanes did not affect fatigue performance.
- o All-graphite/epoxy vanes provided a 24.2 kgs (53 lb.) weight savings compared to aluminum vanes in a typical JT9D engine.
- o Mechanical property tests of four lots of 345 GPa (50 M) modules Fortafil 5A Great Lakes Carbon fiber revealed good repeatability and acceptable properties.
- o Infrared signature and glass transition temperature characterization were established for resin systems.

- o Low voltage radiography and visual examination were effective in identifying most of the intentional and unintentional flaws in as-fabricated vanes. Radiography identified cracks in post-fatigue test vanes.
- o Composite vane price, based on projections of 1000 vanes/month production, was determined to be cost effective based on price-to-weight comparison of composite to current bill-of-material aluminum.

6.2 RECOMMENDATIONS

The following tasks are recommended prior to service evaluation of composite fan exit guide vanes.

- o Determine performance behavior and durability of parts in an experimental engine program.
- o Qualify an alternate (50 million) modulus core fiber.
- o Develop a repair procedure for composite vanes.

APPENDIX A

GRAPHITE FIBER-EPOXY RESIN COMPOSITES SPECIFICATION (PWA 125)

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1. SCOPE:

1.1 Form: Graphite fiber/epoxy resin composite moldings used in structural applications.

1.2 Application: Primarily for fan exit guide vanes operating at temperatures within the range of -54 to 120°C (-65 to 250°F).

2. APPLICABLE DOCUMENTS: The following publications form a part of this specification to the extent specified herein; the latest issue shall apply.

2.1 Pratt & Whitney Aircraft Publications: Available from Purchasing Department of Pratt & Whitney Aircraft Group, East Hartford, Connecticut 06108 or West Palm Beach, FL 33402.

2.1.1 Specifications:

PWA 300	Control of Materials, Processes and Parts
PWA 370	Engineering Source Approval
PWA 443	Graphite Fiber Tape and Sheet

2.1.2 Materials Control Laboratory Manual:

Section E-XXX Microstructure of Graphite Fiber Composite

2.2 ASTM Publications: Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pa. 19103.

ASTM D790 Test for Flexural Properties of Plastics

ASTM D792 Tests for Specific Gravity and Density of Plastics by Displacement

ASTM D2344 Test for Apparent Horizontal Shear Strength
of Reinforced Plastics by Short Beam Method

ASTM D2734 Test for Void Content of Reinforced Plastics

3. TECHNICAL REQUIREMENTS:

3.1 Pre-Production Requirements: Shall be in accordance with PWA
PWA 300.

3.1.1 Detailed process sheets for molding processes shall be
approved by the applicable Engineering Department of the
Pratt & Whitney Aircraft Group before shipment of each new
configuration.

3.1.2 Conformance to pre-production requirements does not relieve
the supplier of responsibility for continued conformance to
all purchase order requirements.

3.2 Materials: Properties of graphite fibers, epoxy resins,
fiber-resin composites and articles molded therefrom shall be as
specified in 3.2.1, 3.2.2, and 3.2.3. Test procedures shall be
as agreed upon by the applicable Engineering Department of the
Pratt & Whitney Aircraft Group and the vendor.

3.2.1 Graphite Fibers: Shall be as specified by this specification
number and a suffix number as follows:

Property and Test Procedure		Low Modulus Graphite Fiber	High Modulus Graphite Fiber
3.2.1.1	Tensile Properties, 24°C ± 3 (75°F ± 5)		
	Tensile Strength, min 2.54 cm (1 in) gage length	2480 MPa (360 ksi)	2200 MPa (320 ksi)
	Tensile Modulus, min	207 GPa (30x10 ⁶ psi)	331 GPa (48x10 ⁶ psi)
3.2.1.2	Density,		
	ASTM D792	1.74 ± 0.05 g/cc	1.80 ± 0.05 g/cc
3.2.1.3	<u>Fiber-Resin Composite:</u> Graphite fibers when formed into a unidirectional 60% ± 6 fiber volume aggregation of graphite fibers with epoxy resin cured in accordance with 3.2.2 shall have the following properties:		

Property and Test Procedure	Low Tensile Modulus Fiber Composite	High Tensile Modulus Fiber Composite
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- | | | | |
|-----------|--|-------------------------------------|-------------------------------------|
| 3.2.1.3.1 | Void Content, max
ASTM D2734 | 3 Vol % | 3 Vol % |
| 3.2.1.3.2 | Density,
ASTM D792 | 1.58 \pm 0.05 g/cc | 1.60 \pm 0.05 g/cc |
| 3.2.1.3.3 | 0° Flexural Strength, min
24°C \pm 3 (75°F \pm 5°F)
Normalized to 60 volume
percent fiber
ASTM D790 Method 1 | 1510 MPa
(220 ksi) | 1000 MPa
(145 ksi) |
| 3.2.1.3.4 | 0° Flexural Modulus, min
24°C \pm 5 (75°F \pm 3)
Normalized to 60 volume
percent fiber
ASTM D790 Method 1 | 115 GPa
(17x10 ⁶ psi) | 152 GPa
(22x10 ⁶ psi) |
| 3.2.1.3.5 | Shear Strength, min
24°C \pm 3 (75°F \pm 5)
Normalized to 60 volume
percent fiber | 93 MPa
(13.5 ksi) | 69 MPa
(10 ksi) |
- 3.2.1.4 Adhesion of Polyurethane Coating: Shall be determined by a method approved by the applicable Engineering Department of the Pratt & Whitney Aircraft Group and when determined at 24°C \pm 3 (75°F \pm 5) shall average 1.4 KN/m (8 lb/in) peel strength with no individual test less than 1.0 KN/m (6 lb/in).
- 3.2.1.4.1 Polyurethane coating adhesion requirements are independent of graphite fiber tensile modulus.
- 3.2.2 Epoxy Resin: Shall be a liquid novolac epoxy adhesive having the following characteristics:
- 3.2.2.1 Storage Life: The product shall meet the requirements of this specification when tested at any time up to 6 months from date of shipment, provided material has been stored under manufacturer's recommended storage conditions.
- 3.2.2.1.1 Material which has been stored under above conditions for more than 6 months shall be reinspected within 5 days of use and conform to the requirements of this specification.
- 3.2.2.2 Properties of Cured Materials: Shall be as follows when resin is cured at 175°C \pm 6 (350°F \pm 10) for 1 hour or at conditions agreed upon by P&WA and vendors.

3.2.2.2.1 Tensile Properties, 24°C \pm 3 (75°F \pm 5)

Tensile Strength, min	48 MPa (7000 psi)
Elongation, min	1.5%
Tensile Modulus, min	3.4 GPa (500,000 psi)

3.2.2.2.2 Density,
ASTM D792 1.25 \pm 0.05 g/cc

3.2.2.2.3 Glass Transition Temperature
Dry, min 166°C (330°F)
Wet, 1.4-1.5 wt % water, min 143°C (290°F)

3.2.2.2.4 Moisture Absorption
Three weeks at 60°C \pm 3 (140°F \pm 5) 1.8 wt %
and 95% relative humidity or equivalent moisture level, max

3.2.3 Composite Articles: Shall consist of graphite fibers with properties as in 3.2.1, bonded with epoxy in accordance with 3.2.2 and, when required, polyurethane coated using process approved by the applicable Engineering Department of the Pratt & Whitney Aircraft Group.

3.2.3.1 Fiber Content, Distribution and Structure: Shall have 60 volume % \pm 5 graphite fiber content and shall conform to microstructural requirements of Pratt & Whitney Aircraft Group, Manufacturing Division, Materials Control Laboratory Manual Section E-XXX.

3.2.3.2 Composite Article Properties: Shall be as follows according to tensile modulus of graphite fibers.

Property and Test Procedure	Low Tensile Modulus Fiber Composite Article	High Tensile Modulus Fiber Composite Article
3.2.3.2.1 Void Content, max ASTM D2734	3 Vol %	3 Vol %
3.2.3.2.2 Density, ASTM D792	1.58 \pm 0.05 g/cc	1.60 \pm 0.05 g/cc
3.2.3.2.3 Flexural Strength, min 24°C \pm 3 (75°C \pm 5) Normalized to 60 volume percent fiber ASTM D790 Method 1		895 MPa (130 ksi)

- 3.2.3.2.4 Flexural Modulus, min
 24°C ± 3 (75°F ± 5) 145 GPa
 Normalized to 60 percent (21x10⁶ psi)
 volume fiber
 ASTM D790 Method
- 3.2.3.2.5 Shear Strength, min
 24°C ± 3 (75°F ± 5) 69 MPa
 Normalized to 60 percent (10 ksi)
 volume fiber
 ASTM D2344
- 3.2.3.2.6 Adhesion of polyurethane coating shall be in accordance with 3.2.1.4.
- 3.3 Quality: Articles shall be uniform in quality and condition, and free from surface or internal imperfections detrimental to fabrication, appearance, or performance of parts.
- 3.3.1 Parts shall not be repaired by plugging, bonding or other methods without written permission from the applicable Engineering Department of the Pratt & Whitney Aircraft Group.
4. QUALITY ASSURANCE PROVISIONS:
- 4.1 Control: Shall be in accordance with PWA 300.
- 4.2 Approval: Engineering Source Approval shall be in accordance with PWA 370 for graphite fiber, epoxy resin and polyurethane coating materials, and for graphite fiber-epoxy resin composite tape and molded composite articles.
5. PREPARATION FOR DELIVERY:
- 5.1 Identification: Each container shall be permanently and legibly identified as follows:
- GRAPHITE/EPOXY COMPOSITE ARTICLES
 PWA 125D
 PART NUMBER
 QUANTITY
 MANUFACTURER'S IDENTIFICATION
- 5.2 Packaging: Containers shall be prepared for shipment in accordance with commercial practice to ensure carrier acceptance and safe transportation to the point of delivery. Packaging shall conform to requirements of carrier rules and regulations acceptable to the mode of transportation.

6. ACKNOWLEDGMENT: Vendor shall mention this specification number and its revision letter in all quotations and when acknowledging purchase orders.
7. REJECTIONS: Material not conforming to this specification or to authorized modifications will be subject to rejection.
8. NOTES:
 - 8.1 Marginal Indicia: Due to the extensive changes in specification requirements from the previous issue, no changes are indicated by the phi (ϕ) symbol.

APPENDIX B-1

TRW MANUFACTURING PLAN

1. INTRODUCTION

This document defines the materials, tooling, fabrication and inspection methods used in the fabrication of thirteen (13) composite fan exit vanes (PWA Drawing No. 762788). This effort was conducted under NASA Lewis Contract NAS3-21037 and PWA subcontract 21037-2 by the Materials Technology Department of TRW Equipment, Cleveland, Ohio.

2. VANE DEFINITION

Two types of vanes were fabricated and designated Type I, all graphite reinforced, and Type II, graphite/glass reinforced. The thirteen vanes were serialized as follows:

<u>S/N</u>	<u>Type</u>	<u>Description</u>
1-00A	I	Tool Verification Vane
1-001	I	Intentional Defect Vane
2-001	II	Intentional Defect Vane
1-002 thru 1-006	I	Prototype Vanes for Fatigue Testing
2-002 thru 2-006	II	Prototype Vanes for Fatigue Testing

3. MATERIALS AND CONSTRUCTION

	<u>Type I</u>	<u>Type II</u>
Core		
Reinforcement	Great Lakes Fortafil 5A	Great Lakes Fortafil 5A
Orientation	0°	0°
Shell		
Reinforcement	Hercules AS-2	Owens-Corning S-2 Glass Roving
Orientation	+30°	+45°
Composite Matrix (both types)		
Resin	Dow Chemical	DEN 438, DEN 331
Curing Agent	Uniroyal	Tonox 60/40
Leading Edge (both types)	10 mil aluminum to AMS-4015	
Polyether Polyurethane Film	PWA 634 (J.P. Stevens MP-1890)	
Polyurethane Adhesive	Dayton Chemical	Thixon AB-1153-66

With both type vanes the outer two plies of shell members were wrapped around the vane trailing edge and buried under the leading edge protector.

4. TOOLING

4.1 Assembly

Following cutout, core and shell plies were assembled on a curved surface simulating the airfoil configuration on which the stacking axis had been scribed so as to align the plies.

4.2 Mold

Using a composite vane provided by PWA designated Part No. 762788 STD 30791 S/N 18 as a master, a soft (tooling epoxy) tool was constructed. This tool consisted of a punch and die conforming to the concave and convex surfaces of the vane airfoil. The tool was integrally heated with electric resistance heating blankets below the mold surface with appropriate thermocouples to monitor and control temperatures.

4.3 Polyurethane Bonding

A special tool was used to conform the polyurethane film to the surfaces of the vane during the secondary bonding cycle. The tool was designed such as to assure a smooth contour around the leading and trailing edges and to preclude or minimize seams and joints.

5. PRELIMINARY PROCESS ROUTING

5.1 Leading Edge

Operation No.

- 010 Issue Aluminum Stock for appropriate vane part number.
- 020 Cut to Size.
- 030 Break at Centerline to 45° fold.
- 040 Form contour.
- 050 Anodize per AMS-2470 (no seal).
- 060 Sodium Dichromate Seal.
- 070 Store in clean plastic bag and identify part S/N on which it is to be used.

5.2 Prepreg (Graphite and Glass, general)

Operation No.

- 010 Drum wind fiber to prescribed lead (see sub-routings).
- 020 Cut 91.5 cm (3 ft) sample of fiber and place in envelope identifying material, lot, date.
- 030 Weigh and mix resin constituents to prescribed formulation (see sub-routing).
- 040 Impregnate fiber (see sub-routings).

- 050 Place 50 ml sample of resin solution in vial and identify by date.
- 060 Stage prepreg to required handling conditions.
- 070 Cut from drum and store in plastic bags at -18°C (0°F) storage. Identify Lot No. by TRW Lab book page and date.

5.3 Assembly

- 010 Issue prepreg from refrigerated storage and bring to room temperature.
- 020 Cut plies per ply maps for shell and core.
- 030 Store in plastic bags until ready for assembly.
- 040 Assemble ID half on convex lay-up tool core and two inner shell plies centered on stacking line starting with shell plies on lay-up tool.
- 050 Assemble OD half on concave lay-up tool as per Operation 040.
- 060 Remove OD half and assemble with ID half on convex tool aligning stacking line.
- 070 Cold preform in mold.
- 080 Assemble two outer shell plies together.
- 090 Conform shell plies to core preform.
- 100 Issue leading edge from stock.
- 110 Clean inside with MEK.
- 120 With small brush, apply matrix resin solution to inside surfaces of leading edge.
- 130 Air dry for 30 minutes.
- 140 Assemble leading edge to vane preform.
- 150 Apply identification and S/N plate to center of air-foil ID.

5.4 Mold

- 010 Install preform in mold.
- 020 Close die and connect power and controls.
- 030 Insert into 93°C (200°F) preheated platen press and apply 690 KPa (100 psi) or 2730 kgs (6000 lbs).
- 040 Raise temperature of mold with heating elements to 93°C (200°F) under pressure.
- 050 Hold 20 mins. after 93°C (200°F) reached.
- 060 Raise temperature to 150°C (300°F) and hold two hours.
- 070 Reduce pressure to 172 KPa (25 psi) or 680 kgs (1500 lb load) and loosen mold rails.
- 080 Cool to room temperature.
- 090 Remove from mold and remove flash.
- 100 Collect resin flash and place in envelope identifying with part S/N and date.

- 110 Postcure vane in air circulating oven. Heat up to 150°C (300°F) at 19°C/hr (35°F/hr). Hold 16 hours. Cool to room temperature.

5.5 Inspection

- 010 Visual inspect vane and record irregularities.
020 Measure pitch thickness with micrometer at inboard and outboard end of vane and record in vane data log.
030 Weigh vane to nearest 0.1 gram and record.
040 Radiographic examination--identify with vane S/N.

5.6 Polyurethane Application

- 010 Issue vane from stock.
020 Lightly sand airfoil surfaces with 300 grit paper and wipe with MEK.
030 Cut polyurethane to designated size with cutting template and shield.
040 Gently wipe polyurethane on side to be bonded with acetone.
050 Dilute Thixon AB-1153 adhesive with C-711 solvent 1:1.
060 Apply wet coat of adhesive to vane by spray.
070 Air dry 30 minutes.
080 Apply second coat of adhesive.
090 Air dry 10 minutes.
100 Apply polyurethane film around vane with joint on concave surface.
110 Wrap release film around vane to retain polyurethane butt positioning and tape in place.
120 Install vane in vacuum bag.
130 Connect to vacuum system and check for leaks.
140 Place in circulating air oven 1 hour at 135°C (275°F) under 11 cm (28 in) hg vacuum minimum.
150 Remove from oven, cool to room temperature and remove from tool.
160 Trim excess film from ends.
170 Visual inspect.

6. QUALITY ASSURANCE PROGRAM

6.1 Raw Materials

Materials were procured under vendor certification, copies of which will be made available to PWA upon request. Vendor test data were included with the certification and identified with lot and batch numbers.

Samples of fiber and matrix resin were secured from each lot of prepreg and provided to PWA.

6.2 Laminates and Testing

Before vane fabrication began, unidirectional panels approximately 2.03 mm (0.080 in) thick were fabricated from each fiber/resin combination (total 3) from which flexural and short beam shear properties were determined at room temperature and 121°C (250°F). Samples from these or equivalent panels 10 x 20 cm (4 x 8 inches) were provided to PWA for their evaluation. Resin content and fiber volume determinations were made. A test panel was fabricated and tested for flexure and short beam shear properties for each batch of prepreg prepared thereafter. Angle ply laminates to which polyurethane film has been adhered were also provided to PWA.

6.3 First Part Testing (S/N 1-00A)

The first vane fabricated and master vane used to fabricate mold was plotted at 5X magnification at three sections (D-D, J-J and X-X) and compared to 5X EMD charts (provided by PWA) and the charts from the master vane. The part was radiographed and dimensionally inspected for pitch thickness.

6.4 Defect Vanes

One vane of each type (S/N's 1-001 and 2-001) was fabricated with intentional defects. The defects were of the following types and achieved as described below:

- A. Core matrix cracking - simulated with 10 mil Teflon inserted in core in an orientation normal to airfoil surface.
- B. Interply Delamination - simulated with round discs of 0.5 mil Teflon 0.635 cm (1/4 in) and 0.952 cm (3/8 in) diameter.
- C. Resin Rich Area - simulated by inserting precast 5 mil shims of matrix resin 0.635 cm (1/4 in) and 0.952 cm (3/8 in) diameter.
- D. Porosity - simulated by a syntactic foam of phenolic microballoons with matrix resin at 10 mil thicknesses. Size to the 0.635 cm (1/4 in) and 0.952 cm (3/8 in) diameter.
- E. Trailing Edge Fiber Misalignment - the outer shell plies will be loosely wrapped around the trailing edge in an attempt to disrupt orientation.
- F. Polyurethane/composite unbond - simulate with 0.5 mil Teflon 0.635 cm (1/4 in) and 0.952 cm (3/8 in) diameter.

6.5 Quality Control Records

A vane data log will be used to record, by serial number, significant material and process information. The data log will contain a process routing and provision for recording the date of process events, material batch identities, process information, inspection data and operator comments.

6.5.1 Sub-Routing Section

Prepreg Preparation - Fortafil 5A Graphite Fiber

Equipment: Entec Winder

Set-Up Details: Ply Thickness 0.26 mm (10.2 mils)/ply
Lead 16.2 mm (0.641 in)/turn (Lot CT 5896 & 5897)
TPI 1.56

Gears (Fiber) $\frac{BDF}{ACE} = \frac{39}{25} \times \frac{20}{25} \times \frac{100}{100}$: (Resin)

$$\frac{64}{25} \times \frac{76}{20} \times \frac{100}{81}$$

Resin Solution (25 w/o)

DEN	438A-85	58.8 gms (0.13 lbs)
DER	331	50.0 (0.11)
Tonox	60/40	20.0 (0.04)
Acetone		351.0 (0.77)

One prepreg sufficient for 9 vane cores plus 2 unidirectional panels 21.6 x 21.6 x 0.20 cm (8.5 x 8.5 x 0.080)

Operations

010	Set up winder to required lead and spreader details.
020	Wind and spread fiber to give 104 cm (41 in) of useable material. Log weight fiber used.
030	Remove 91.5 cm (3 ft) sample of fiber and place in sample envelope with date, fiber type and lot No.
040	Set up change gears and metering pump with resin solution and calibrate to give discharge rate of 63.6 gm/min 2.2 oz/msi) at 10 rpm.
050	Apply resin.
060	Retain sample of resin solution and store in refrigerator with date.
070	Air dry with drum turning for 2 hours.
080	Apply release paper to top of prepreg.
090	Cut prepreg from drum 90° to fiber direction.

- 100 Cut prepreg into 10 circumferential lengths 44.4 cm (17.5 in) each. Retain tag end, about 33 cm (13 in) for prepreg tests.
- 110 Stage.
- 120 Cut 10 sets of core ply maps from ozalids.
- 130 Adhere ply templates to prepreg and cut in half along ply line between plies No. 12 and No. 13.
- 140 Bag in packages for each panel and vane, identify and store in -18°C (0°F) storage. Store tag end separately.

6.5.2 Sub-Routing Section

Prepreg Preparation - Hercules A-S Graphite Fiber

Equipment: Entec Winder

Set-Up Details: Ply Thickness 0.13 mm (5.1 mil)/ply
 Lead 5.69 mm (0.224 in)/turn (A-S Lot 76-2)
 TPI 4.45

Gears (Fiber) $\frac{BDF}{ACE} = \frac{41}{25} \times \frac{44}{20} \times \frac{100}{81}$: (Resin)

$$\frac{64}{25} \times \frac{76}{20} \times \frac{100}{81}$$

Resin Solution (25%)

DEN 438 A-85	58.8 gms (0.13 lbs)
DER 331	50.0 (0.11)
TONOX 60/40	20.0 (0.04)
Acetone	351.0 (0.77)

Prepreg #1 45.7 cm (18 in) wide unidirectional panels (2) and core of polyurethane test panel.

Prepreg #2 86.3 cm (34 in) wide vane shell and angle plies for polyurethane test panel shell.

Operations

- 010 Set up winder to required lead and spreader details.
- 020 Apply release paper to drum for two prepreg sheets.
- 030 Wind fiber for prepreg #1 45.7 cm (18 in) wide.
Wind fiber for prepreg #2 76.2 cm (30 in) wide.
- 040 Remove 91 cm (3 ft) sample of fiber and place in sample envelope with date, fiber type and Lot No.

050 Set up new change gears and metering pump with resin solution and calibrate to give discharge rate of 25.6 gm/min 0.90 oz/msi) at 10 rpm.

060 Apply resin.

070 Retain sample of resin solution and store in refrigerator with date.

080 Apply release paper to top of prepreg.

090 Cut off prepreg #1 90° to fiber.

100 Cut prepreg #1 into 6.9 cm (17.5 in) lengths, package and store in -18°C (0°F) storage. Retain tag end 33.0 cm (13 in) long for prepreg tests.

110 Stage.

120 Cut prepreg #2 from drum at +60° (clockwise direction).

130 Cut prepreg #2 into nine 53 cm (20.9 in) circumferential lengths.

140 Splice pieces to form 30° oriented material.

150 Cut oriented material into ten 73.7 cm (29 in) lengths.

160 Stage.

170 Bag individually, identify and store in -18°C (0°F) storage. Include tag end.

6.5.3 Sub-Routing Section

Prepreg Preparation - Owens-Corning S-2 Glass 12 End Roving Fiber

Equipment: Entec Winder

Set-Up Details: Ply Thickness 0.13 mm (5.1 mils)/ply
 Lead 2.09 mm (0.0822 in)/turn
 TPI 12.16

Gears (Fiber) $\frac{BDF}{ACE} = \frac{64}{25} \times \frac{76}{20} \times \frac{100}{80}$: (Resin) Same as Fiber

Resin Solution (25%)

DEN 438 A-85	58.8 gm (0.13 lbs)
DER 331	50.0 (0.11)
TONOX 60/40	20.0 (0.04)
Acetone	351.0 (0.77)

Prepreg #1 Unidirectional panels (2) and core of polyurethane panel.

Prepreg #2 Vane shell and angle plies for panel shell.

Operations

- 010 Set up winder to required lead and spreader details.
- 020 Apply release paper to drum for two prepreg sheets.
- 030 Wind fiber for prepreg #1 45.7 cm (18 in) wide
Wind fiber for prepreg #2 86.3 cm (28 in) wide
- 040 Remove 91.5 cm (3 ft) sample of fiber and place in
sample envelope with date, fiber type and Lot No.
- 050 Set up metering pump with resin solution and calibrate
to give discharge rate of 30.9 gm/min (1.09 oz/min) at
10 rpm.
- 060 Apply resin.
- 070 Retain sample of resin solution and store in refriger-
ator with date.
- 080 Apply release paper to top of prepreg.
- 090 Cut off prepreg #1 45.7 cm (18 in) wide at 90° to
fiber.
- 140 Cut prepreg #1 into 44.5 cm (17.5 in) length, package
and store in -18°C (0°F) storage.
- 150 Stage.
- 160 Cut prepreg #2 from drum at +45° (clockwise).
- 170 Cut prepreg #2 into seven 62.86 cm (24.75 in) lengths.
Retain 38.1 cm (15 in) tag end for 2/4/2 panels.
- 180 Splice pieces to form 45° oriented material.
- 190 Cut oriented material into nine 76.2 cm (30 in)
lengths.
- 200 Stage.
- 210 Bag individually, identify and store in -18°C
(0°F) storage. Include tag end which is 38.1 cm (15
in) long. This piece will be used for shell plies of
polyurethane test panel.

6.5.4 Sub-Routing Section

Test Panel Fabrication

Identification

Unidirectional Panels:

Materials:	Fortafil -5A	8 plies
	Hercules A-S	16 plies
	Owens-Corning S-Glass	16 plies

Construction: Unidirectional 21.6 cm x 21.6 cm x 0.203 cm (8.5
in x 8.5 in x 0.08 in)

Angle Ply Panels:

Materials: Hercules A-S
Owens-Corning S-Glass

Construction:

<u>No. Plies</u>	<u>Material/Orientation</u>	
	<u>A-S</u>	<u>S-Glass</u>
Shell 2	+30°	+45°
Core 4	0°	0°
Shell 2	+30°	+45°

Material Utilization

For the panels to be made use material from prepreg prepared for vanes as follows:

0° Fortafil 5A panel: Use one 44.5 cm (17.5 in) long length of prepreg which will make 8 plies.

0° Hercules A-S: Use eight lengths of 45.7 cm (18 in) wide by 44.5 cm (17.5 in) long from Prepreg #1.

0° Owens-Corning S-Glass: Use 8 lengths of 45.7 cm (18 in) wide by 44.5 cm (17.5) inch long from Prepreg #1.

2/4/2 Hercules A-S:

Core: Use two lengths of 45.7 cm (18 in) wide by 44.5 cm (17.5 in) long from Prepreg #1.

Shell: Use one length of Prepreg #2. Cut off corner and splice to make up to 6 plies 30°.

2/4/2 S-Glass:

Core: Use two lengths of 45.7 cm (18 in) wide by 44.5 cm (17.5 in) long from Prepreg #1.

Shell: Use 38.1 cm (15 in) (circumferential) length from Prepreg #2. Cut off corner and splice to make 4 plies at 45°.

Panel Fabrication

0° Panels	Cut plies 21.6 cm x 21.6 cm (8.5 x 8.5 in) 8 plies of Fortafil 5 16 plies of A-S and Glass
2/4/2 Panels	Cut plies 21.6 cm x 21.6 cm (8.5 in x 8.5 in) Assemble +, -, 0, 0, 0, 0, -, +

Mold and postcure to prescribed cure schedule.

APPENDIX B-2

COMPOSITES HORIZONS MANUFACTURING PLAN

1. INTRODUCTION

This Manufacturing Plan outlines general manufacturing procedures and quality assurance methods for the fabrication of Pratt & Whitney part number 762788 thick trailing edge Fan Exit Guide Vanes. This effort is part of PWA subcontract 21037-1 of PWA Contract NAS 3-21037.

1.1 Fan Exit Guide Vane Description, P/N 762788

The thick trailing edge Fan Exit Guide Vanes built by CH for PWA under subject contract are of two types. Both utilize a graphite/epoxy unidirectional core and an oriented shell utilizing the same epoxy matrix. One configuration employs a graphite/epoxy shell while the other uses an S-glass cloth/epoxy shell. In both cases the shell plies are continuous around the trailing edge of the vane as it is fabricated.

2. APPLICABLE DOCUMENTS

The following documents define requirements for the production of Fan Exit Guide Vanes.

PRATT & WHITNEY AIRCRAFT

PWA 125C
PWA 300Y
PWA 370
PWA Drawing P/N 762788

COMPOSITES HORIZONS

Latest revisions of the following:

CH 74-48 Engineering Processes Specification
746038 EFF and related Manufacturing Shop Orders

3. GENERAL FABRICATION

The following sections define the general fabrication procedures and materials for fabricating Fan Exit Guide Vanes of the thick trailing edge configuration. The sections cover the basic types of operations grouped in the same fashion as the Manufacturing Shop Orders from which they are taken. Figure 1 displays the basic manufacturing flow plan for vane fabrication providing a key to the sections which follow.

3.1 Resin Preparation

This section defines the procedures for the resin used in the manufacture of prepreg for the PWA Fan Exit Guide Vanes.

3.1.1 Resin Mix Operations

Obtain resin constituents from stores

Verify acceptability of materials and record acceptance tag numbers on resin batch traveler.

Using a calibrated scale, weigh each constituent and record its weight on the data sheet.

Mix with mechanical agitation and visually observe for uniformity.

Assign the next available batch number to this mix. Record the batch number and date mixed on the traveler.

Q.C must accept each resin batch to CH 74-48A.

3.2 Pultrusion

This section establishes the pultruding of graphite/epoxy material for FEGV.

A traveler shall be issued for each pultrusion run.

3.2.1 Setup Of Creel

Obtain required number of rolls of graphite from stores.

According to the instructions on Data Sheet Number 1 attached to the traveler, locate the rolls of fiber on the creel spindles.

As each roll is placed on a spindle, record the information for the roll required by Data Sheet Number 1.

After all rolls are located, inspect creel setup.

3.2.2 Threading of Fiber

Remove outer wrapping from the rolls of fiber.

Starting at tier A on the creel and the highest spindle number on tier A, thread the graphite tow through the eyelet directly below the spindle.

Proceed to Tier A-1 and repeat.

Proceed progressively until all tiers are complete.

Position guide roller rack.

Thread the fiber through the dies.

Prior to starting a pultrusion run, the temperature of the dies is to be verified.

3.2.3 Pultrusion Run

Begin the pull and note visually that fiber is running smoothly through the dies.

After a constant pulling force has been established, record the pulling force.

Identify the beginning of the pultrusion length with the lot number and the number -1.

3.2.4 Disposition Of Pultruded Material

Each length of pultrusion shall be placed in a plastic bag and marked with pultrusion number and consecutively 1, 2, 3, etc., with the number 1 assigned to the first section.

The sections may be used once accepted by Q.C. or placed in storage.

3.3 Broadgoods

This section defines the machine setup, materials and fabrication procedures for the manufacture of graphite/epoxy and glass/epoxy broadgoods.

The broadgoods are used as shell ply material in the manufacture of Fan Exit Guide Vanes.

The machine setup is to remain constant throughout the manufacture of all broadgoods. Quality control is to verify periodically that the machine setup remains constant.

For graphite broadgoods, check the lead by engaging the lead screw and rotating the drum recording the traverse.

3.3.1 Drum Guide Lines

Move the carriage to a position where the payoff roller is near the left end of the machine and a right travel greater than 89 cm (35 in) can be attained.

Engage the lead screw to provide travel to right.

Using the trim lines "N" and "S" establish the trim angle for graphite broadgoods.

3.3.2 Release Film Setup

Obtain release film from stores and keep in area until used.

Cut release film to required size and shape using guidelines on broadgoods cutting table. (The same size sheet may be for both type "N" and "S" graphite broadgoods). Separate release film is required for glass/epoxy broadgoods due to the difference in trim angle.

Place a 2.54 cm (1 in) wide double backed tape on the drum approximately centered on the appropriate trim line.

Apply the release sheet smoothly to the drum.

3.3.3 Broadgoods Winding

Obtain a reel of graphite (or ply of glass fabric) from stores and record the required data on the Broadgoods Record Sheet.

For glass, roll the fabric evenly onto the drum and proceed with resin application.

For graphite, install the material on the reel holder.

Move the carriage to position the payoff roller in line with the starting point for winding.

Thread the tow through the pins and guide roller.

Attach the tow to the drum.

Engage the lead screw to provide travel away from the starting point.

Turn the machine on and wind the required number of turns.

3.3.4 Resin Application

For graphite broadgoods, at the end of the winding, rewind the excess graphite onto the spool.

Obtain the resin required from the resin mix station, record the batch number, date mixed and acceptance tag number.

Check the shelf life expiration date. If the material is out of date, MRB approval must be made before the resin is used.

Weigh out the required amount of resin.

Apply the resin to the broadgoods.

Impregnation is complete when all the resin is uniformly distributed.

3.3.5 Broadgoods Removal

Using a razor knife, cut through the broadgoods at the trim line.

Bring a support board into the winding enclosure to support the broadgoods as it is removed.

Peel the upper portion of the broadgoods from the machine and place it over the support board.

Gradually rotate the drum so that the broadgoods slides onto the board.

Transfer the support board and broadgoods to the cutting table and slide the broadgoods onto a storage board.

Visually inspect the broadgoods for resin wetting and gapping. Broadgoods may be used once accepted by Q.C. or placed in storage.

3.4 Shell Plies

This section defines the preparation of bias oriented shell plies PWA Fan Exit Guide Vanes.

These plies are used to fabricate P/N 762788 Vanes.

Verify acceptability of broadgoods fabricated to S.O. 746038 B/G prior to fabricating plies.

3.4.1 Fabrication Of Shell Plies

Place a broadgood (B/G) on the B/G cutting table.

Bring the long edge of the B/G to the edge locating land.

Using a straight-edge cutting bar and a razor knife trim the B/G along the cutting line.

Lift the cutting bar and slide the trimmed edge forward to the index line.

Place the cutting bar on the cutting line and cut a strip of B/G using the bar as a guide.

Repeat until the B/G is consumed.

Using the length index, cut the strips to the correct size.

Take a Q.C. Sample from the B/G. Identify the strip with the B/G number and give this strip to the leadman for evaluation.

Using a felt-tip pen, write the B/G serial number on the release film side of each ply.

3.4.2 Laminating Shell Plies

Stack the required number of plies for the shell in the orientation sequence given in the Shop Order.

Using the shop aids provided, fold the ply set into the wrap-around configuration and complete laminating as described in the Shop Order (746038LP).

3.4.3 Ply Cutting - Final Shape

Take a ply set and lay it on the cutting table.

Place the template marked plies 3 and 4 on the ply set so that the long straight edge of the template is aligned with the folded edge of the material and the ply angle line is parallel with the angle of the fibers.

Using a razor knife, trim along the curved edge of the template.

Repeat for plies 1 and 2 on the same side of the ply set.

Write the ply numbers on the release film.

Invert the ply set and place the template marked 38 and 39 on the set so that the long straight edge of the template is aligned with the folded edge of the material and the ply angle line is parallel with the angle of the fibers.

Using a razor knife, trim along the curved edge of the template.

Repeat for plies 40 and 41. On the same side of the ply set write the ply numbers on the release film.

3.5 FABRICATION

This section establishes the layup, molding and finishing of graphite epoxy and glass/epoxy shell guide vanes.

3.5.1 Preparation Of Core

Draw from stores a sufficient number of cores for one day's usage.

Obtain a set of shell plies from stores.

3.5.2 Layup

Smooth the plies into the layup tool.

Note for gaps which would denote improper mating to layup tool.

Place the core over plies 3 and 4.

Fold plies 38 and 39 onto core.

Note gaps.

Smooth plies 38 and 39 against the core, with hand pressure.

Remove the preform from the layup tool and inspect.

Preforms may be placed in cold storage or processed further at this point.

Note the vane number on a piece of onion skin about 0.95 cm (3/8 in) wide and 1.9 cm (3/4 in) long, and affix to the vane concave surface.

Verify all data is recorded on the preform data sheet.

3.5.3 Molding

Clean the mold periodically, as required.

At the start of the shift, open the press and inspect the mold surfaces.

At the start of the shift, apply a thin coat of mold release. Repeat after every 8 to 10 moldings, or as needed to ensure good release.

At the start of each shift and every 4 hours during use, verify the temperature of the mold using a calibrated instrument for this purpose, recording the temperature.

The temperature shall be within tolerance prior to beginning molding.

Place preform in the mold and start timing when preform hits the mold.

Close the press and raise the pressure to full pressure.

Cure for the required time.

Just prior to opening press, measure opening at each stop, if any.

Open the press and remove the molded vane.

Allow to cool to room temperature.

Visually inspect the vane.

Remove flash.

Clean all vane surfaces. Air dry 10-15 minutes. Polyurethane application must be done within one hour of cleaning.

3.5.4 Polyurethane Film Application

Obtain polyurethane film from stores.

Place the film in the coating fixture and insert vane.

Remove and insert into the bonding fixture.

Note: At the start of a shift, verify accuracy of mold temperature.

Remove from bonding fixture at completion of cycle.

Inspect vane for polyurethane adhesion.

Submit vane to Quality Control for inspection.

4. QUALITY ASSURANCE PROVISIONS

4.1 Equipment And Tooling

A schedule shall be prepared by Quality Assurance for periodic checking of accuracy of equipment and process parameter levels to insure accuracy and conformance of equipment and processes to the engineering process specification for Fan Exit Guide Vanes.

4.2 Receiving Inspection

All graphite, glass, resin constituents and related raw materials will be inspected and accepted prior to use in the fabrication of Fan Exit Guide lines.

4.3 In-Process Inspection

All materials including pultruded and broadgood Gr/Ep & Gl/Ep used in direct fabrication of vanes will be continually monitored to assure the quality of the fabricated vanes. This will include chemical tests, process parameter inspection and material handling and storage inspection as required throughout the fabrication process.

4.4 Process Records

The Manufacturing Shop Order/data sheets shall contain information necessary for the complete tracing of all constituent materials, processing parameters, processing dates, operator identification and inspection buy-offs.

4.5 Final Inspection

CH will assure vanes to be of experimental quality and will final inspect every vane in the following areas:

1. Vane length
2. Chord (M dimension)
3. T.E. thickness (U dimension)
4. L.E. thickness (V dimension)
5. T.E. radius
6. L.E. radius
7. Shield edge distance
8. Ply overlap, gaps
9. Urethane coverage
10. General visual
11. Weight
12. Urethane peel
13. Torsional spring rate (Except tool proof, NDI Vanes)
14. Bending spring rate (Except tool proof, NDI Vanes)

CH will provide PWA with inspection records of each vane delivered. Vane contour inspection will be performed at PWA as CH does not have contour gage slides for the thick trailing edge configuration FEGV, P/N 762788.

4.6 Non Destructive Inspection Standard - PWA P/N 762788 FEGV

The vane defects NDI standard will be processed as a regular vane, using all of the physical parameters for standard vanes. Defects (Table I) will be introduced during the layup of the vane and just prior to molding.

TABLE I

1. T.E. SHELL POROSITY/INCLUSION
2. CORE/SHELL DISBOND
3. MISALIGNED CORE FIBERS
4. CORE RESIN POOL
5. CORE/SHELL INTERFACE RESIN POOL
6. MISALIGNED SHELL PLYS
7. SHELL PLY GAP
8. SHELL POROSITY
9. CORE MATRIX CRACKING

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3. "Primer on Composite Materials Analysis", Ashton, J.E., Halpin, J.C. and Petit, P.H., Progress in Materials Science Series, Vol. 3, Technomic Publishing Co., Stamford, Conn., 1969.
4. "Advanced Composites Design Guide - Volume 1" - Contract No. F33615-74-C-5075.
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LIST OF SYMBOLS

E_{11}	- modulus of elasticity, longitudinal direction
E_{22}	- modulus of elasticity, transverse direction
f_B	- natural frequency of first bending mode of vibration
f_T	- natural frequency of first torsion mode of vibration
G_{12}	- modulus of elasticity in shear
K_B	- bending stiffness
K_T	- torsional stiffness
RH	- relative humidity
T_g	- glass transition temperature
w/o	- percent water content by weight
$\epsilon_{MX\ THK}^X$	- strain in the longitudinal (radial) direction of the FEGV at maximum airfoil thickness on the convex surface
ϵ_{TE}^X	- strain in the longitudinal direction at the trailing edge on the concave surface
ϵ_{TE}^Y	- strain in the transverse (chordwise) direction at the trailing edge on the concave surface
TE	- trailing edge
LE	- leading edge

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